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FORECASTING GUIDE NO. 3

Hurricane Forecasting

by

Staff Members
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PREFACE

Many members of the Weather Bureau's forecasting and research staff participated in the preparation of this Guide. It is not possible to acknowledge by name all of those taking part, but it is appropriate to mention those who made some of the more substantial contributions to its production. The principal authors were as follows: Banner I. Miller, Paul L. Moore, and Gilbert B. Clark of the Miami Office, and D. Lee Harris and the undersigned of the Central Office. The appendices were prepared principally by Robert H. Simpson of the National Hurricane Research Project and Donald L. Jorgensen of the Central Office. Other contributions to the writing of portions of the Guide were made by José A. Colón of the San Juan Office and Eugene W. Hoover, Robert A. Hoover, and Conrad P. Mook of the Washington (Airport) Office. Significant advice and comment on organization and content were given by Gordon E. Dunn and Emanuel M. Ballenzweig, both of whom also contributed some hitherto unpublished illustrative material for inclusion here. William H. Haggard and George W. Cry provided the latest available climatological information, some of which is also being published here for the first time.

JAY S. WINSTON
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Hurricane Forecasting

INTRODUCTION

SCOPE OF GUIDE

This guide is designed to acquaint Weather Bureau meteorologists with the various aspects of the prediction of hurricanes and other well-defined tropical storms. To achieve this goal without making this guide inordinately voluminous, details of actual application of the various methods are kept to a minimum in the main body of the text. However examples of the application of several methods for forecasting storm motion are given in the appendices. Although this guide is not intended to serve as a complete manual for the hurricane forecaster, it should form a good basic framework around which a hurricane forecasting manual can be built. From the very title of this publication it is obvious that only the forecasting of tropical cyclones is emphasized here; hurricane structure and mechanics, observational and analysis details, and other aspects of tropical forecasting are treated only briefly insofar as they provide better understanding of problems and methods of hurricane forecasting. Most of the geographical emphasis throughout the guide, particularly in the climatological information, is on the Atlantic and North American areas where the Weather Bureau's primary hurricane forecasting interests and responsibilities lie. However, most of the forecasting methods are applicable to other regions where tropical storms occur; indeed much of the information and many of the ideas used in hurricane prediction were obtained from tropical cyclones of other areas, particularly the typhoons of the Pacific region. The material covered here includes most of the sound forecasting procedures now in use at Weather Bureau Hurricane Forecast Centers, and also many newer ones which have been devised in the past few years and which may have had only limited tests. The purpose of including these newer approaches, even though they are not fully tested, is to give the reader a good survey of the latest thinking on hurricane forecasting problems. Naturally it is expected that many new forecasting ideas will be devised and tested in the next few years, particularly with the increased emphasis on hurricane research since the inception of the National Hurricane Research Project. It is hoped that this guide will serve to bring the reader up to date on hurricane forecasting and that he will keep himself informed on future developments by carefully following research results as they are published in the meteorological journals.

IMPORTANCE OF THE HURRICANE PROBLEM

Examination of statistics concerning loss of life and property damage resulting from hurricanes emphasizes the urgent need for the best possible hurricane warning service. In the period 1942-1957 the average number of lives lost in hurricanes in North and Central America each year has been 270. The average for the United States alone has been 63. While there has been no loss of life com-

Table 1 - Some disastrous tropical storms affecting the United States in the twentieth century. Number of deaths over the United States and adjacent waters is given.

Year	Area Severely Affected	Number of Deaths
1900	Galveston	6,000
1915	Mid-Gulf Coast	275
1919	Florida, Louisiana, Texas	787
1926	Miami	243
1928	West Palm Beach-Lake Okeechobee	1,836
1935	Florida Keys, Tampa	408
1938	New England	494
1944	New Jersey, Long Island, New England	390
1954	Long Island, New England (Hurricane Carol)	60
1954	South Carolina to Canadian Border (Hurricane Hazel)	95
1955	Northeastern States (Hurricane Diane)	184
1957	Gulf Coast of Louisiana and East Texas (Hurricane Audrey)	392

parable to the catastrophes of some other countries, such as India, the United States has been afflicted with a number of disastrous tropical storms. The worst of these in terms of death tolls were the Galveston hurricane of 1900 and the West Palm Beach--Okeechobee hurricane of 1928. These and other devastating tropical storms, which have affected the United States since the beginning of the twentieth century, along with the death toll resulting from each, are listed in table 1.

Property damage associated with hurricanes is difficult to assess, particularly on a comparative basis in view of the changing value of the dollar. However, by any standards, the cost to the economy of direct and indirect damage from tropical storms is staggering and there is no doubt that through the years this has shown a great increase with population and industrial growth. The total property damage in the United States directly attributable to hurricanes in the period 1942 through 1957 totaled about two and a half billion dollars. This is a conservative figure, which is probably less realistic than an estimate including indirect economic losses as well. As examples of the latter one may cite the materials and labor involved in securing property against the storm and the production time lost from the time storm preparations begin until repairs have been made, all of which must add up to a considerable sum. It was at one time estimated that it cost a single large chemical plant on the Gulf coast $500,000 to $750,000 whenever hurricane warnings were issued.

An east coast hurricane may pose a threat to as much as 1000 miles of coastline and perhaps as many as twenty million people. In addition to the interruption of the industrial life of a community when warnings are issued, there are many other problems involved including the psychological aspects. For instance, overwarning can cause needless alarm and as an eventual result can lower public confidence in the forecasts with risk of dangerous inaction in response to subsequent warnings.

Although it is impossible to give specific figures on the reduction of loss which can be credited to precautionary measures based on warnings, it is undoubtedly true that the improved hurricane warning service in recent years has resulted in huge savings in life and property. From the very large magnitude of the economic losses in hurricanes nowadays it can be seen that if the warnings improve only very slightly the savings could amount to perhaps a few million dollars. Obviously the opportunities and the need for effecting savings in casualties and property damage will increase with population growth and further concentration of people and industries in coastal and other communities vulnerable to the destructive forces of the hurricane.

CLASSIFICATION, LIFE CYCLE, AND STRUCTURE OF TROPICAL CYCLONES

Classification of Tropical Cyclones According to Intensity

The nomenclature of tropical cyclones varies considerably. At times such terms as "tropical cyclone", "tropical storm", and "hurricane" are used almost interchangeably with little regard for differences in size or intensity. For the most part, however, the terms are used to denote intensity of systems. The Weather Bureau* considers three categories of non-frontal cyclones of tropical origin, all of which must show evidence of a closed circulation at the surface. These are distinguished in terms of observed or estimated surface wind speeds associated with the systems as follows:

Tropical depression - maximum winds less than 34 kt (39 mi/hr).

Tropical storm - maximum winds 34 to 63 kt (39 to 73 mi/hr) inclusive.

Hurricane (typhoon in western Pacific) - maximum winds 64 kt (74 mi/hr) or higher.

Life Cycle of the Hurricane

The life cycle of a hurricane is usually divided into four stages as follows:

The formative stage - starts with the birth of the circulation and ends at the time that hurricane intensity is reached. In this stage the minimum pressure reached is about 1000 mb.

The immature stage - lasts from the time the system reaches hurricane intensity until the time it reaches its maximum intensity in winds and lowest central pressure. The lowest central pressure often drops well below 1000 mb and the wind system becomes organized in a tight ring around the eye with a fair degree of symmetry. The cloud and precipitation fields develop into narrow, inward-spiraling bands.

The mature stage - lasts from the time the hurricane attains its maximum intensity until it weakens to below hurricane intensity or transforms to an extratropical cyclone. In this stage the hurricane may exist for several days at nearly the same level of intensity or decrease slowly. The storm grows in size, with strong winds reaching farther and farther from the center. The weather and winds

*Chapter B-50, Vol. III of the Weather Bureau Manual.

usually extend farther in the right semicircle of the storm. By the time a hurricane reaches the mature stage it is usually well advanced toward the north and west, or else it has already recurved into the westerlies. The typhoons of the Pacific Ocean usually last longer in the mature stage and grow to larger sizes than the hurricanes of the Atlantic.

The decaying stage - may be characterized by rapid decay as in the case of many storms which move inland, or by transformation into a middle-latitude cyclone. In the former case the storm steadily loses strength and character. In cases of transformation there is frequently a regeneration in middle latitudes which results in maintenance or redevelopment of strong winds and other hurricane characteristics.

There is no set duration for the time a hurricane may be in any one stage. It is entirely possible that a hurricane will skip one stage or go through it in such a short time that it is not distinguishable with the available synoptic data. On some occasions it is even difficult to identify the stage of development of a given storm. By and large, however, hurricanes do go through a life cycle that can be divided into these four stages.

Structure

Knowledge of the typical structure of tropical storms is particularly important in the analysis of a storm and in many phases of its prediction. Detailed information on a given storm's structure may, or may not, lead directly to improved methods for predicting its future motion and development, but this remains to be determined when observations within the storm become much more complete and accurate. At any rate it is generally conceded that forecasting will be aided at least indirectly by better knowledge of storm structure since more realistic theoretical models of tropical cyclones will then be feasible.

Since details about the structure of tropical storms have been summarized very well in the recent textbook by Riehl [125] and also in other recent studies [115, 160], no general treatment of hurricane structure will be given here. However, characteristics such as pressure, surface winds, rainfall, and effects on the sea surface are so closely interwoven with the prediction of these elements that some pertinent structural aspects of hurricanes will be covered below in the various sections dealing with these problems.

CLIMATOLOGY OF TROPICAL STORM OCCURRENCE

The climatology of tropical storms and their behavior serves as extremely valuable background information for the hurricane forecaster. In fact, at some stages in the life cycle of a hurricane the currently available forecasting tools are indecisive or conflicting and climatology becomes one of the forecaster's principal prediction guides. Climatological information on hurricanes has been derived for most of the various aspects of the hurricane problem, so the pertinent climatology will be treated under the various topics discussed below. At this introductory point, however, it is appropriate to present some of the more general climatological information on annual and monthly frequencies of occurrence of tropical storms in the North Atlantic area (including the Gulf of Mexico and the Caribbean).

Tropical storm frequencies vary considerably on an annual basis. This is demonstrated in figure 1 (taken from [156]) where the annual frequencies for the period 1887 to 1957 are graphed. There have been as many as 21 storms in one year (1933) and as few as 1 storm (1890 and 1914), but the median number per year is 8. Note that the median annual number of storms during roughly the middle of this 71-yr period, 1910-1930, was only 4 as contrasted with a median number of 8 in the period 1887-1909 and 10 in the period 1931-1957. Certainly this latter period has seen a distinctly higher level of tropical storm activity, particularly with respect to the 1910's and 1920's. These long-term fluctuations to a great extent must be related to the fluctuations in the atmospheric general circulation and to such related factors as variations in sea-surface temperature. Some of the relationships to circulation patterns will be treated later in the section on formation and intensification. In regard to sea-surface temperatures, a recent investigation by Riehl [126] suggests that there may be some positive correlation between 5-yr averages of sea-surface temperatures and 5-yr hurricane frequencies in the Atlantic area, but the relationship is a relatively poor one at best. There have also been suggestions that secular fluctuations in tropical storm activity are related to quasi-periodic variations in solar activity. Willett [160] has attempted to demonstrate that the sunspot cycle, through its possible effects on the general circulation, may account for some of the longer-period variability in tropical storm frequency and motion in the Atlantic area. These investigations into the causes of variations in tropical storm frequency are very far from conclusive.

Monthly frequencies of tropical storm occurrence during this 71-yr period (1887-1957) are summarized in [156] and are shown in table 2. Note that 546, or 97 percent, of the storms occurred during six months, June through November. These are the months, therefore, which are usually termed "the hurricane season" in the North Atlantic area.

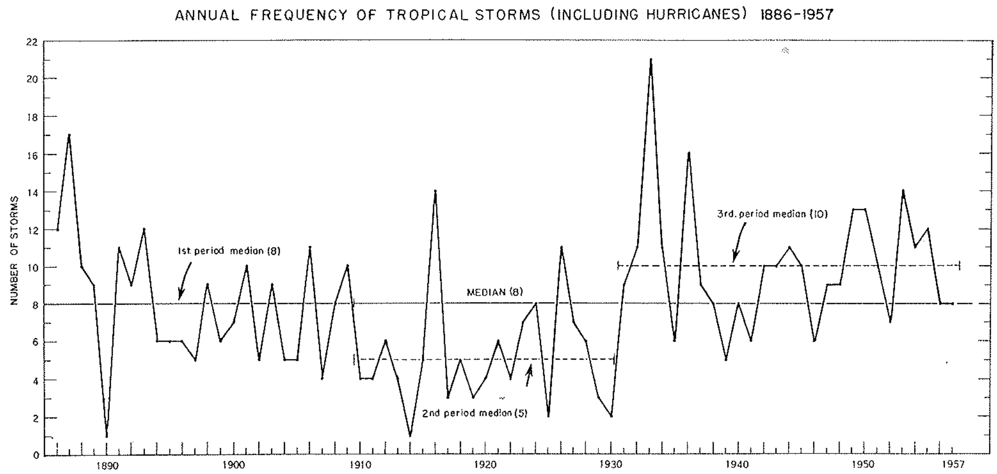


Figure 1. - Annual frequency of tropical storms (including hurricanes) in the North Atlantic Area 1887-1957.

September is the month of most frequent tropical storm activity by a wide margin. However, August and October have high frequencies too, and taken together the occurrences in these three months comprise about 80 percent of all storms. When only those tropical storms of hurricane intensity are considered, the general rank of the various months in frequency remains nearly the same.

Table 2 - Numbers of tropical storms and hurricanes in North Atlantic area (including Gulf of Mexico and Caribbean), 1887-1957 arranged by months. (From [156]).

Month	Tropical Storms	Number Reaching Hurricane Strength
January	0	0
February	1	0
March	1	1
April	0	0
May	9	2
June	33	14
July	38	20
August	127	94
September	187	119
October	135	62
November	26	11
December	4	2
Totals	561	325

However, there is one important difference - August exceeds October in the number of hurricanes by a sizeable margin and it even runs a relatively close second to September which, of course, has the most hurricanes. Considering this in another fashion, the likelihood of a given tropical storm being or becoming a hurricane in August is 74 percent, while in September it is 64 percent and in October only 46 percent.

Table 3 gives further details of this monthly variation in tropical storm occurrence. It shows for each month the percentage of times in this 71-yr period that each of the various numbers of storms has been observed. This figure is in the upper left corner of each box of table 3. In addition, cumulative percentages are presented in the lower right corner of each box. These give the percentage of the months in which at least that number of storms has occurred. For example, in August there were 3 storms 14 percent of the time and 3 or more storms occurred 23 percent of the time. Assuming this 71-yr sample is fairly representative, the figures in table 3 can be used as probabilities of the various numbers of storms that may be expected in any of these months.

A few of the specific features of table 3 are worth brief comment. Note that in August the occurrence of 2 storms has been most frequent, although 1, 0, and 3 also have occurred rather frequently. In September there are actually maxima at 1 and 3, but essentially there is a very wide range in the number of storms in this month, with anywhere from 1 to 4 storms occurring with relatively high frequency. Incidentally, the highest frequency in

Table 3 - Percentage frequencies of the number of tropical storms occurring in the North Atlantic area during each of the months, June - November, in the period 1887-1957. The percentage frequency for each number of storms appears in upper left of each box. Figure in lower right is percentage of months in which at least the given number of storms occurred.

Number of Storms	Month											
	June		July		August		September		October		November	
0	62		59		18		3		14		66	
1	31	38	31	41	24	82	27	97	25	86	32	34
2	6	7	7	10	35	58	17	70	32	61	0	2
3	1	1	3	3	14	23	25	53	20	29	2	2
4	0	0	0	0	4	9	20	28	4	9	0	0
5	0	0	0	0	2	5	5	8	2	5	0	0
≥ 6	0	0	0	0	3	3	3	3	3	3	0	0

any month in this 71-yr period occurred in September - 7 storms in 1949. In October, 2 storms have occurred most frequently, but 1, 3, or 0 are also not too infrequent. In June, July, and November the non-occurrence of a tropical storm is most frequent, but if any do occur, it is quite rare that there will be more than 1.

Annual and monthly variations in total tropical cyclone frequency in the eastern North Pacific off the coasts of Mexico and Central America are not up to date. Available data up to 1940 (cf. [25]) show a monthly variation similar to the Atlantic with a maximum of storms in September and relatively high frequencies in August and October. One notable difference from the Atlantic area is that the frequencies in June and July are nearly as high as August and October.

Frequencies for other regions of the world may also be found in [25]. The outstanding area for tropical storm occurrence is, of course, the western North Pacific, where tropical cyclones occur with a moderate frequency even in winter, and where the peak season might be considered as starting in early summer and extending into early winter.

THE WEATHER BUREAU HURRICANE FORECASTING SERVICE

HISTORY

The federal weather service in the United States was established in 1870 under the Army Signal Corps. One of its first duties was the issuance of warnings in connection with tropical storms. The weather service began receiving reports from Havana, Santiago de Cuba, and Kingston, Jamaica, about August 1873, and what were probably the first hurricane warnings were issued in the form of cautionary signals from Cape May, New Jersey to New London, Connecticut on August 23, 1873, for a storm offshore. The first Signal Corps weather map to show a hurricane indicated one off the coast between Savannah and Jacksonville on September 28, 1874. The network of observations useful to hurricane reporting was greatly improved when on July 7, 1889 Congress passed a bill authorizing the establishment and operation of stations throughout the West Indies and around the Caribbean.

On October 1, 1890 the organic act creating the Weather Bureau was approved with responsibility for its operation assigned to the Department of Agriculture. Prior to 1898 warnings had been issued only for United States coastal areas, but in that year the Spanish-American War created a demand for warnings for shipping and the military. The Hurricane Warning Service was organized at that time with the establishment of a forecast center in Kingston, Jamaica, which was transferred to Havana in 1899. All areas of the West Indies were given the benefit of the service, as they have been to this date.

In these early days forecasting of hurricane motion was based primarily on tide indications and cloud movements with local barometer readings used as short-range signs. At least as early as 1895 forecasters had some idea of antecedent conditions for hurricane formation. Garriott [34] stated that the first indications in the West Indies were abnormally high pressure and unusually cool, clear weather, preceding the storm by several days. He also recognized the effects of dynamic anticyclogenesis in connection with hurricanes and listed a number of empirical rules relating recurvature to the movement of extratropical systems.

In 1902 the Hurricane Service was transferred to Washington and shortly afterwards hurricane forecasting took an important stride forward with the development of radio and the possibility of obtaining weather reports from ships at sea. The first of these was received in 1905 and the first to indicate a hurricane was from the S.S. Cartago near the coast of Yucatan on August 26, 1909. The marine observations program was steadily expanded until by 1935 more than 21,000 ship observations were received from the hurricane area of the Atlantic during the six months that constitute the hurricane season (June-November).

As a result of this increasing data supply Bowie [9] was able to publish in 1922 a rather comprehensive study of hurricane formation and movement. He showed that forecasters of that day considered both the convective theory and the effect of impulses from middle latitudes in explaining formation. He also found that winds at 3 to 4 km in the right front quadrant of the storm were representative of the wind system that carried the hurricane and that except for variations caused by passing systems to the north, a hurricane tended to follow the outer isobar of the subtropical high. As more pilot balloon observations became available, refinements were made in the technique of correlating hurricane movement with upper winds. Norton [109], for example, applied the concept of a "steering level", which was chosen on the basis of the intensity or stage of development of the storm.

In a major reorganization of the Hurricane Warning Service in 1935 centers were established in Jacksonville, New Orleans, and San Juan, and continued in Washington. Along with this decentralization, a continuous 24-hr watch was instituted for the hurricane season and a special hurricane teletypewriter system was set up between Jacksonville and Brownsville. At the same time, ship and coastal observations were increased to four a day. The upper-air program was gradually improved, and in 1937, with the establishment of the radiosonde network, more complete upper-air information enabled forecasters to begin forecasting movement and changes in direction with a higher degree of confidence. In 1943 aircraft reconnaissance was found to be feasible when Col. J. P. Duckworth flew into the eye of a hurricane in the Gulf of Mexico [150]. The following year Air Force and Navy planes began reconnaissance of hurricanes on a fairly routine basis. Nighttime reconnaissance is a more recent development made possible by the use of radar.

In 1943 the Jacksonville center was transferred to Miami. Meanwhile a center for the New England area had been established at Boston. Miami was selected as the location for the Joint Hurricane Warning Central (with participation by the Weather Bureau, Air Force, and Navy), which was given responsibility for coordination of all hurricane advisories.

CURRENT ORGANIZATION

Basic instructions for the operation of the Hurricane Warning Service are outlined in Chapter B-50, Vol. III of the Weather Bureau Manual. In addition, certain other procedures are included in the annual Hurricane Warning Service Agreement between the Weather Bureau, Navy, and Air Force, in the manual of operations for teletypewriter circuit 7021, and in various circulars that are issued from time to time as new developments or requirements arise. Since most of these publications are generally available, only a brief survey of the current forecast organization will be given here.

Hurricane forecast centers responsible for issuing advisories and warnings for tropical storms in the Atlantic, Caribbean, and Gulf of Mexico areas are located at San Juan, New Orleans, Miami, Washington, and Boston. The areas of responsibility for these centers are shown in figure 2.

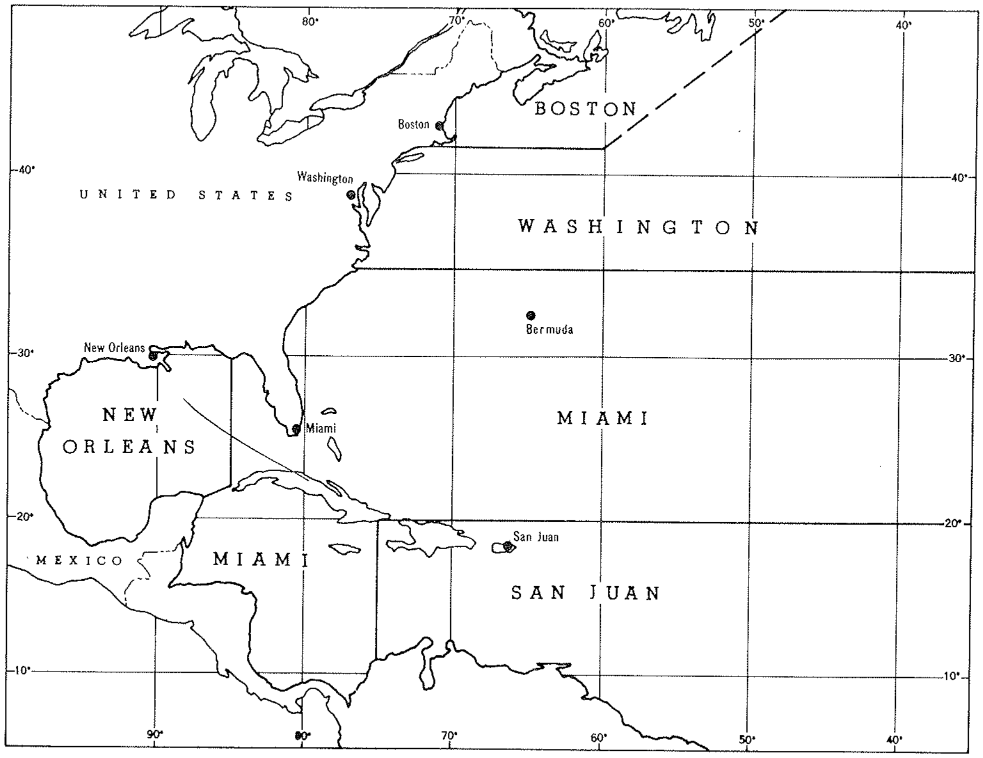


Figure 2. - Weather Bureau Hurricane Forecast Centers and areas of hurricane warning responsibility, Atlantic Area.

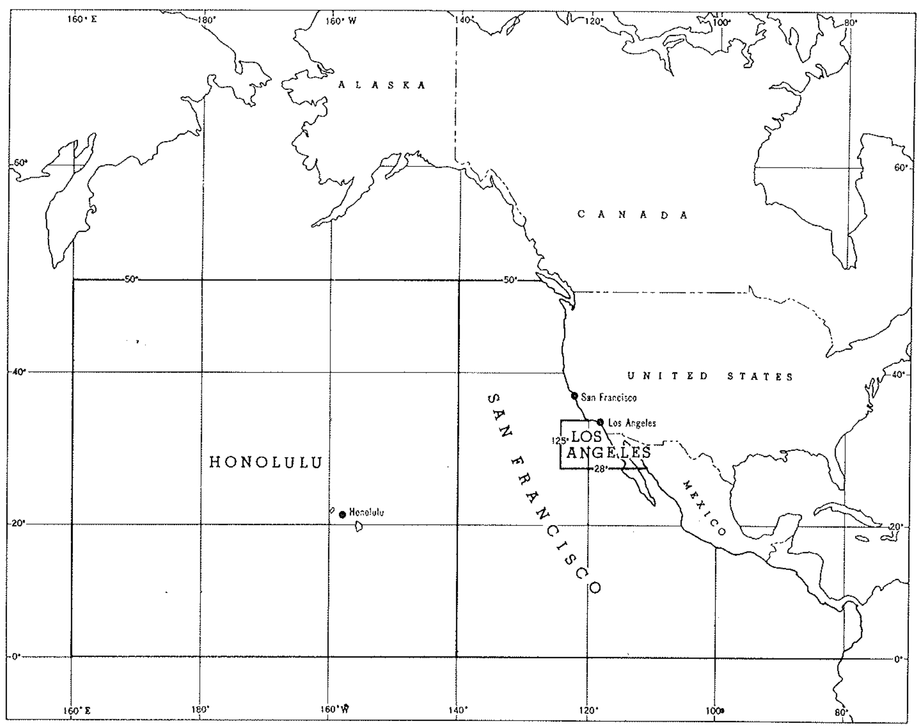


Figure 3. - Weather Bureau Hurricane Forecast Centers and areas of hurricane warning responsibility, Pacific Area.

Advisories for tropical storms in the Atlantic north of 35°N are issued and included in marine weather bulletin broadcasts as long as the storms are west of longitude 35°W. South of 35°N advisories are issued as far east as available reports permit detection and tracking of the storm. While a formal display of warnings is not ordered by the Weather Bureau for the islands of the Caribbean, except under a few specific local agreements, it is generally accepted that the Weather Bureau is the primary agent for tropical storm warnings throughout the area. The hurricane warning service in the Pacific is assigned to forecast centers at Honolulu, Los Angeles, and San Francisco, areas of responsibility for which are shown in figure 3.

In view of the widespread and serious effects of hurricanes it is important that ideas and advices of the various forecast centers be coordinated to avoid the issuance of conflicting or confusing information to the public. Consequently, when a hurricane is in position to affect more than one area of forecast responsibility in the near future, telephone consultations between forecasters at the responsible centers are held prior to the issuance of advisories and the display of warnings near the boundary of the two areas. Consultations by telephone or teletypewriter are also held between the responsible forecast offices and the National Weather Analysis Center in order to exchange ideas and insure that there are no inconsistencies between NAWAC's analyses and prognoses and the advisories from the hurricane forecast centers. Occasionally representatives of the Joint Numerical Weather Prediction Unit and the Extended Forecast Section also take part in the telephone conferences. Local offices are also included in conference calls or may be called directly when necessary to insure maximum understanding of mutual problems and procedures.

The Miami Office is responsible for coordinating the advisories of all Weather Bureau centers with those of the Navy Weather Central at Miami and for providing the Air Force Hurricane Liaison Officer at Miami with the coordinated advisories. Coordination of aircraft reconnaissance and of requests for special observations from military establishments or from other meteorological services is also a function of the Miami center.

OBSERVATIONAL AIDS FOR DETERMINING STORM POSITION, INTENSITY, AND STRUCTURE

SURFACE AND UPPER-AIR OBSERVATIONS

Data Coverage

Meteorologists have never had sufficient synoptic data available to enable them to regularly prepare detailed analyses for more than small sections of the vast tropical belt at a time. This is true even at the surface, and in regard to the upper air, the situation often seems quite hopeless. During World War II, however, a large amount of upper-air data was collected both in the Caribbean and in the tropical Pacific. Later the nuclear bomb tests in the Pacific provided detailed meteorological observations from a large area, but over a rather limited period of time. These collections of data are still being analyzed.

During the past few years, the establishment of guided missile tracking stations and the operation of the National Hurricane Research Project have provided a more concentrated upper-air network in the Atlantic and Caribbean areas than was ever available before to the tropical meteorologist. The locations of the sounding stations, however, have been confined largely to the island chains, but these observations have been supplemented by aircraft reconnaissance and such information as can be gleaned from commercial pilot reports. Over vast portions of the tropical North Atlantic, however, there are still no upper-air data.

The surface data picture is generally somewhat better, at least in some sections. Numerous ship reports from the Gulf of Mexico, the Caribbean, and the Atlantic area north of the Antilles and west of Bermuda supply much valuable information. However, the area east of the Lesser Antilles is not crossed by a great amount of shipping and much of this area is usually devoid of reports.

Analysis and Interpretation

Surface Synoptic Charts - While great strides have been made during the past decade in the use of such modern developments as reconnaissance and radar in locating tropical storms, the surface synoptic pattern still serves a vital role in giving early indications that a storm is forming and in enabling the forecaster to determine the approximate location of the storm center. Such information can be used as the basis for preliminary warnings, if necessary, and to dispatch reconnaissance aircraft to pinpoint the storm's location and to determine its exact intensity. Since meteorological elements in an undisturbed state within the Tropics vary only slightly, the synoptician has learned to look for small departures from the normal state as evidence that a disturbance exists or is forming. Dunn [25] has summarized much of the present knowledge along this line.

The trade winds, for example, blow steadily over the oceans, from between northeast and southeast at 15-20 kt, and an increase in speed by as much as 25 percent (except where local influences such as the sea breeze reinforce the normal flow) reveals that a disturbed state has developed. Similarly if a ship within the trade-wind belt reports a wind with a westerly component of 10 kt or more, it is a fairly certain sign that a tropical disturbance has developed. The intensity of the cyclone can be estimated from the strength of the west wind.

Atmospheric pressure has a relatively small variability within the Tropics, with the net 24-hr change being normally less in magnitude than the diurnal variations. It has been established empirically that a localized 24-hr pressure fall of 3.0 to 3.5 mb reveals the existence of an unstable wave which may develop into a tropical storm. Likewise, a fall of pressure to a value 5 mb or more below that normally observed (e.g. to about 1007 mb within the Caribbean) may indicate possible cyclogenesis. Such a departure from normal is generally indicative of mass evacuation of the air at high levels, i.e., high-level divergence, not completely compensated by low-level convergence, and consequently any low-level disturbance moving into such an area will be favorably located for rapid deepening.

Since the atmosphere in the Tropics is quasi-barotropic, possessing small lateral temperature gradients and scant slope of the isobaric surfaces, large-scale vertical motions are much smaller than those of the middle latitudes. Consequently precipitation occurs mostly from cumuliform clouds in the form of showers and scattered thunderstorms, with little high cloudiness usually observed. A variation in this regime in the form of solid altostratus clouds, or heavy or steady rainfall, as distinguished from showers, at several adjacent stations indicates that large-scale upward motion at intermediate levels is well organized, which leads the forecaster to suspect that a tropical storm has formed.

Streamline Analysis - In middle latitudes the magnitudes of the pressure gradient and Coriolis forces are such that the frictional and accelerational terms in the equations of motion can usually be neglected without introducing serious error. As the two former terms decrease rapidly south of about latitude 20°N, the latter two approach the same order of magnitude and can no longer be ignored. Jordan [65] compared the observed winds with the geostrophic for low latitudes and found that departures from the geostrophic were small north of 20°N, but south of that latitude over 75 percent of the winds were substantially sub-geostrophic. The departures increased rapidly equatorwards and at 10°N the difference was 9 m/sec, which is greater than the actual wind velocity. Obviously, then, the usual geostrophic wind relationship does not apply very well to the Tropics, and this has led to a direct analysis of the wind field, viz., streamline analysis, with the pressure pattern relegated to a secondary role. Streamline analysis may be applied to either the surface or upper-level charts. When applied at sea level great care must be exercised lest non-representative winds result in an incorrect analysis. The success of the method obviously depends upon a good network of wind observations.

In regions of sparse data little can be accomplished other than a representation of wind directions. Trough lines, shear lines, and centers can be extrapolated from previous charts and approximate streamlines drawn even in areas of very little data. The use of reports from airplane pilots often yields additional information. Only qualitative estimates of divergence and vorticity are obtainable from this type of analysis.

Where the spacing of wind observations is dense, a more elaborate system of streamline analysis can be applied. This was developed by V. Bjerknes and Sandstrom early in the present century, but it was only recently that Palmer et al [115] adapted it for use within the Tropics. After the streamlines are completed, isotachs are added, and from these combined features the fields of divergence and vorticity can easily be computed. Figure 4 illustrates such an analysis for a situation in the Caribbean area and the Gulf of Mexico. Evident in this figure are such typical features of stream flow as singular points, where wind speeds are zero and direction is indeterminate (e.g., the cyclonic vortex off the northwestern Florida coast and the neutral point over southwestern Louisiana), and asymptotes, where streamlines converge or diverge. Another frequent feature of the wind field which does not appear in figure 4 is the shear line, across which wind direction changes virtually discontinuously.

Upper-Air Charts - In the early stages of development tropical storms are occasionally better developed between the 10,000- and 20,000-ft levels than they are at the surface [25]. This probably applies primarily to those storms whose origin is triggered by the mid-tropospheric injection of cold air from long waves in the westerlies into the Tropics in a manner suggested by Namias [104]. Consequently streamline analysis of upper-level wind charts or detailed analysis of the constant pressure charts will occasionally permit an early location of an incipient center. This is particularly important at stations in the Lesser Antilles and at those bordering on the Gulf of Mexico, since the upper-air patterns frequently indicate that a development is taking place over the adjacent

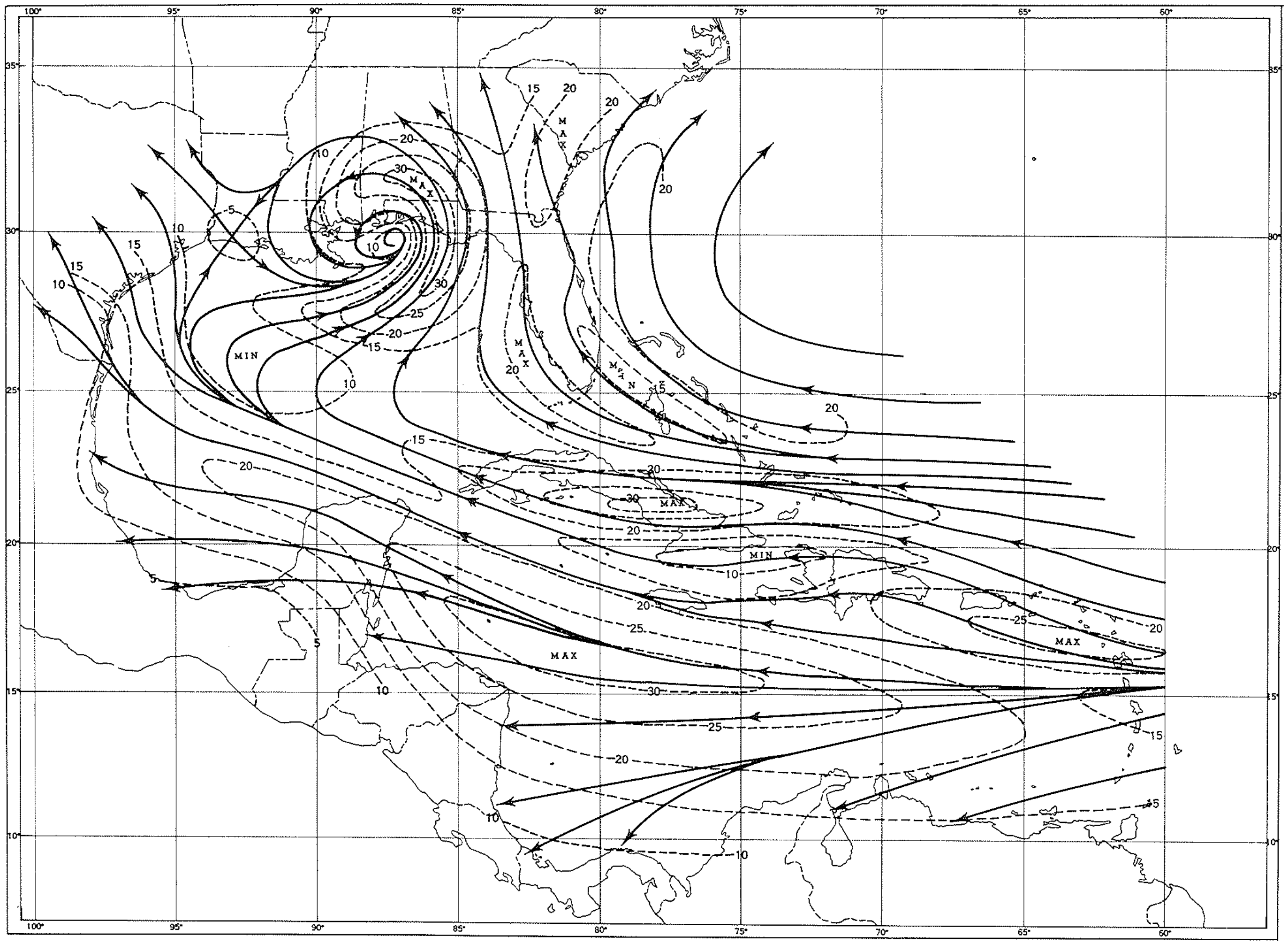


Figure 4. - Streamline and isotach analysis of the field of motion at 2,000 ft over the Caribbean, Gulf of Mexico, and adjacent areas, 0300 GMT, July 7, 1956.

waters long before any surface reports are received to confirm this fact.

Most hurricane centers extend contour analysis of the constant pressure charts all the way to the equator although, as pointed out above, the geostrophic wind relationship is not very accurate south of about latitude 20°N. The use of streamline analysis on constant pressure charts often yields a better picture of the wind field south of about 20°N, but too often there are insufficient wind reports over the particular areas of interest to allow for an adequate analysis based on observed winds alone.

Riehl [125] suggests 850 and 200 mb as the most profitable levels to analyze in the Tropics. These charts have generally been made standard, but the intermediate levels are still employed extensively. Most methods of forecasting the motion of hurricanes, for example, are based on the 500- or 700-mb charts. The influence of high-level vortices on the movement and formation of tropical storms has been studied by Riehl [124] and others. These systems can be followed best on the 200-mb chart.

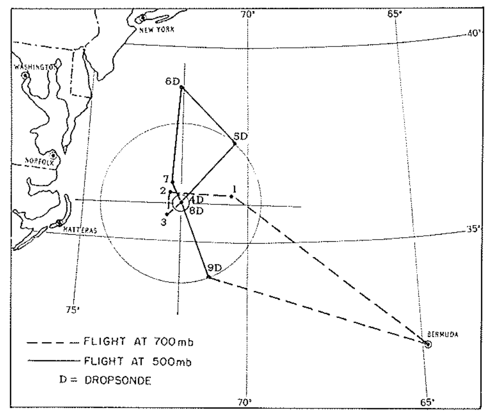


Figure 5. - Typical flight plan of a hurricane reconnaissance flight from Bermuda. Flight is in direction of increasing numbers, with dropsonde releases at points indicated by letter "D". Note that soundings are taken at both traverses of the eye of the storm (points 4 and 8).

RECONNAISSANCE

Hurricane reconnaissance by aircraft has been and will likely continue to be one of the most important tools the forecaster uses. Prior to the 1944 hurricane season, hurricane forecasters had to rely on sparse ship reports (and during wartime virtually none) and a very scattered network of weather reports from island stations in the Tropics. Sometimes the forecaster would go several days without any reports in the vicinity of fully developed hurricanes as compared to several eye fixes by radar and penetration each day during most of the life span of today's hurricane.

Since 1944 a routine reconnaissance flight program has been jointly operated by the Air Force and Navy. Information relayed by these flights has been constantly improving with new type planes and much more accurate weather instruments. Navigation, one of the most difficult problems, has been improved to a very fine degree during the last few years. At the present time, Air Force planes are based at Bermuda while the Navy operates out of Jacksonville and each group has a designated area of responsibility. Flights are generally made at levels between 700 and 500 mb and the structure of the storm is determined by wind reports, heights of the 700- and 500-mb levels, dropsondes and other measurable and visual weather phenomena. A typical plan of a reconnaissance flight from Bermuda is shown in figure 5.

In addition to routine reconnaissance by the Air Force and Navy, the National Hurricane Research Project sent highly instrumented Air Force planes [50] into as many tropical storms (potential as well as actual) as possible during the 1956 and 1957 seasons. Whenever technically feasible three planes were sent into a storm at low, middle, and high levels of the troposphere to map a three-dimensional picture of the storm and to help determine its complete energy budget. Unfortunately they were able to get all three planes in the air in only a few cases; on most occasions only one or two planes were operational. The instruments on these planes provided continuous records of temperatures, humidity, "D" value, wind direction and speed, and vertical motion. Automatic navigation was used and it allowed for very accurate determinations of the plane's position and wind velocities. These data thus permitted fairly complete and accurate analysis of a storm's circulation and weather phenomena. Incidentally it should be pointed out that automatic navigation has also been used by regular Air Force reconnaissance planes since 1956 and will probably be instituted on Navy planes in the near future. Thus wind speeds and directions obtained by reconnaissance aircraft are or will be of rather high accuracy as compared with visual and double-drift methods for obtaining winds, which were used exclusively prior to the last few years.

Reconnaissance reports of heights of the various pressure levels are of considerable aid to the forecaster in determining the intensity and location of a storm. The heights of the pressure levels at which the planes fly are measured from the dif-

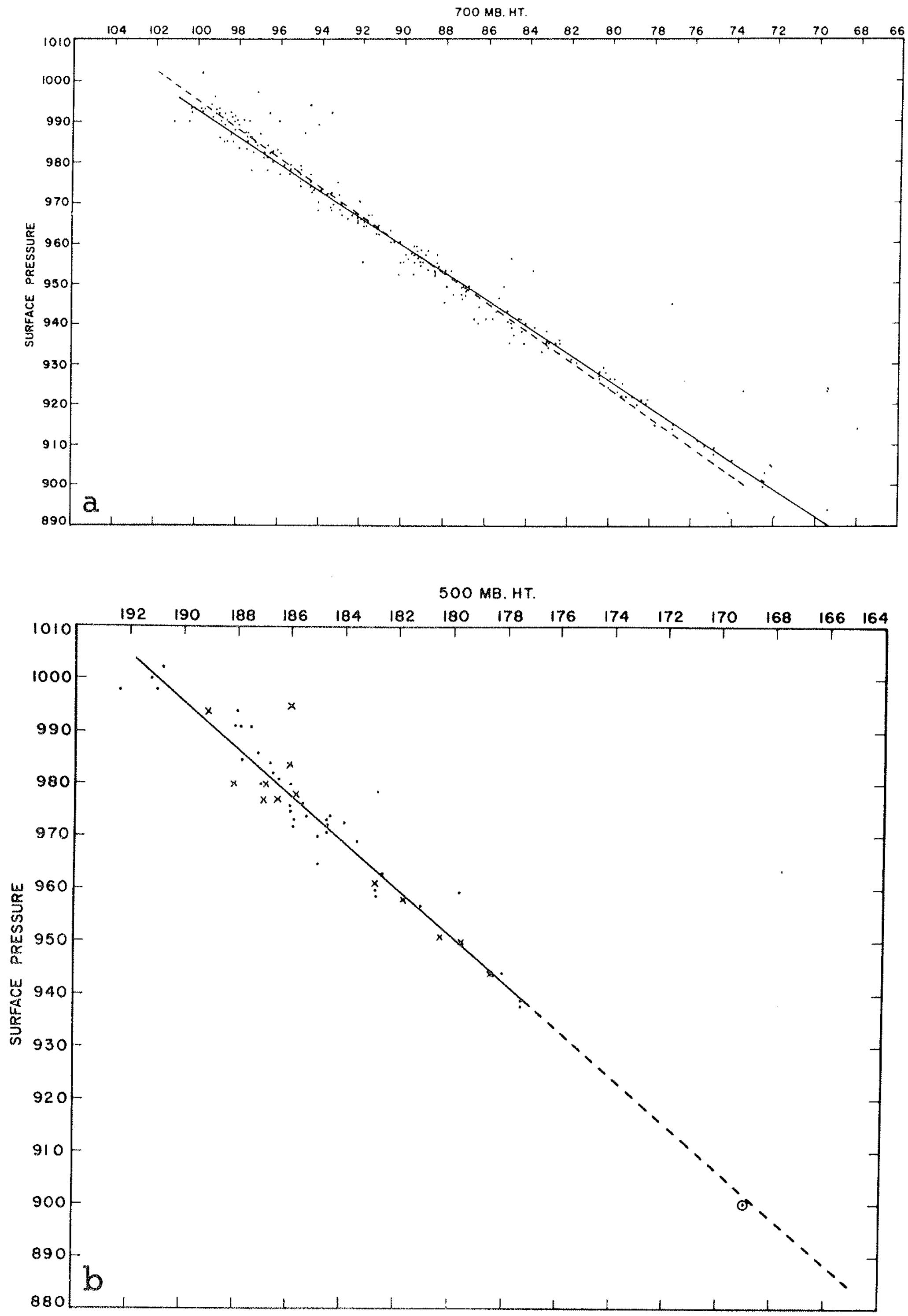


Figure 6. - Surface pressure as a function of (a) 700-mb height and (b) 500-mb height as obtained from dropsondes within the eyes of typhoons (700-mb data) and hurricanes (500-mb data). Solid lines are regression lines for the data shown. Dashed line in (a) is regression line based on earlier set of data. Dashed line in (b) is an extension of solid line to illustrate fit for typhoon Marge of 1951 which is circled in lower right. (After Jordan [67])

ferences ("D" values) between the radio and pressure altimeters. Heights of pressure levels nearer the surface and sea-level pressure are measured by means of dropsondes released by the plane (see figure 5 for scheduled dropsondes in a typical flight). To estimate sea-level pressure at the storm's center when only the 700- or 500-mb height is available, Jordan [67] has developed empirical formulas based on eye soundings. These are graphed in figure 6. Estimates from these graphs are considered reliable south of latitude 30°N and when the storm is not becoming extratropical. These estimates are generally accurate to within 1 to 3 mb as are most other sea-level pressures determined by aircraft.

A tremendous increase in the number of dropsondes by reconnaissance during the last few years has given us a much more thorough knowledge of the temperature field associated with hurricanes [64]. One of the most striking findings was that upper-level temperatures in the eye were considerably warmer than the normal tropical sounding. Figure 7 illustrates a typical eye sounding as compared to the mean West Indies sounding for the "hurricane season" (July-October) [68] and a dropsonde made in typhoon "Marge" in 1951 [143]. As surmised from earlier eye soundings made by land stations, dropsondes have shown that the intensity of storms seems to be directly related to the temperatures around the 500-mb level. Temperature readings by dropsonde are considered fairly accurate, but humidity measurements are still subject to error.

Other significant observations sent by reconnaissance aircraft consist of type and height of clouds, precipitation, icing, and radar summaries. Reports on cloud tops from high-level flights enable the forecaster to get an idea of the intensity of squalls associated with the hurricane and the location of the strongest quadrant of the storm. The location and areal extent of very heavy precipitation are also useful in determining the intensity of the storm. Most of the weather data relayed by the planes are plotted on charts so that the forecaster can get a general synoptic picture at the surface and other levels.

The possibilities of rocket reconnaissance of hurricanes were accidentally discovered in 1954 by pictures made of a weak tropical storm over Texas [58]. Further studies of hurricanes by rocket photography are being made. Also to be attempted in the near future, will be soundings by rocket, which could provide wind, temperature, and density data up to about 200,000 ft. Another observational device soon to be tested is the "hurricane beacon", a balloon-carried transmitting instrument which is designed to stay at the hurricane's center at a constant pressure level, thus providing an automatic means for locating the storm at any time. This beacon would be released from reconnaissance aircraft flying into the eye of the storm.

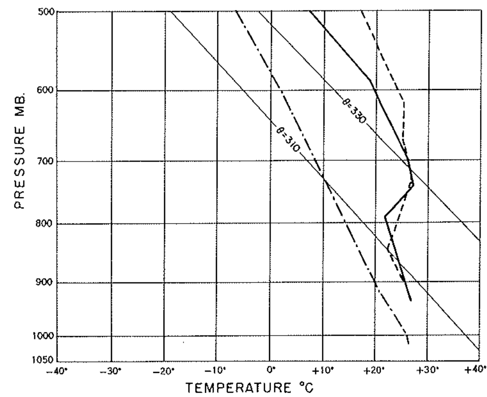


Figure 7. - Typical soundings within the eye of a hurricane or typhoon. Solid line is a dropsonde in hurricane Connie, 1750 GMT, August 8, 1955; dashed line is a dropsonde in typhoon Marge, 1951 [143]; while dashed-dotted line is normal hurricane season sounding for West Indies area [68].

RADAR

Hurricane weather bands, or squall lines, since they penetrate to sufficient heights to reach above the radar horizon at considerable distances and contain great numbers of sizable water droplets, are particularly good subjects for radar viewing. However, prior to the more general use of radar in reconnaissance aircraft, having a radar set within range of a hurricane was strictly a fortuitous circumstance, since installations were so widely spaced and their locations were not usually based upon considerations of weather usage. In 1944 the distinctive pattern of a hurricane was first observed on radar and in 1945 the Air Force radar station at Orlando, Florida, obtained both still and motion pictures of the radar scope as a hurricane moved up the Florida peninsula. Wexler [159] used these pictures to make a comprehensive analysis of the relation of radar echoes to weather distribution in a hurricane. The most striking feature of a radar presentation of a hurricane is the presence of very noticeable arcs of echoes or "spiral bands" (fig. 8). Wexler interpreted these as areas of sizable upward currents, with the intervening spaces as areas of downward motion. Aircraft reconnaissance has verified this

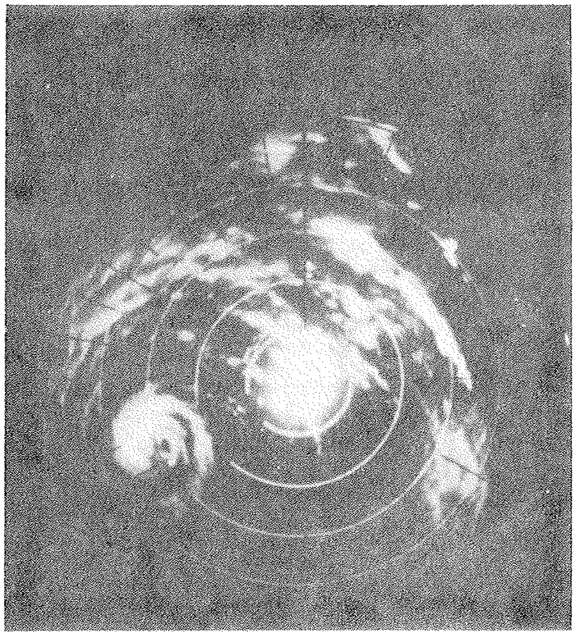


Figure 8. - Photograph of radarscope at Cape Hatteras showing hurricane Connie and its spiral bands, 1132 EST, August 12, 1955. Circular range markers are at intervals of 20 mi.

interpretation. These bands coincide closely with the squall lines associated with hurricanes and are on the order of 3 to 20 mi in width and about 10 times this distance in length. They possess cyclonic curvature and generally spiral toward the center of the storm. Although they at times seem to define the center there is often real difficulty in locating it precisely by simple visual observation. Not only are there fluctuations in the intensity and size of the bands, but parasitic circulations are reflected in the band structure and make it doubtful as to which is the real eye of the storm. It is known that there are, in fact, occurrences of multiple eyes. There is some evidence that, at least in growth stages, movement of the center occurs discontinuously through intensification near the area of greatest curvature of a particularly intense spiral band, at the expense of the original center. Another difficulty in interpreting radar pictures of a hurricane arises from attenuation of the radar beam in heavy precipitation. This causes a distorted picture of the precipitation areas depending upon the location of the radar set with respect to the hurricane, and upon a number of design features, particularly the wave length and peak power of the set.

In spite of these difficulties radar is very useful in many cases in defining the center of the storm's circulation. Recent studies by Senn et al [138, 139] have shown that there is a good relationship between the storm center as indicated by simple logarithmic spiral curves fitted to major spiral bands on radar photographs and the center of the storm determined by other more conventional methods. As a result of this work transparent overlays with a few of these simple logarithmic spirals have been prepared. These can be fitted by eye to a well-defined spiral band on a given radar picture of a hurricane and a good estimate of the location of the storm center can be obtained. These investigators found that the storm center could be located within a radius of 15 naut mi in 83 percent of the cases studied.

Exact movements of the spiral bands relative to the storm have been difficult to establish, but the latest findings [138] show that echoes in the bands tend to move outward across the bands (i.e., in a path more circular than the spiral shape of the bands). Evidence seems to indicate that the bands are developed and maintained by convergence and convective activity originating near the 2,500-ft level. Another interesting finding is that the bands appear to be relatively independent of minor terrain variations.

From the instantaneous and extrapolated positions of these bands that can be obtained by use of radar, very short-range forecasts (for up to a few hours) of the passage of these bands and their associated squalls over given stations can be made. Some of the most severe weather in hurricanes occurs with these spiral-band squall lines. For example, winds in these squalls, even at considerable distances from the center, may approximate velocities in the circular zone immediately surrounding the eye. It has even been suggested that tornadoes in hurricanes are associated with waves on these spiral bands [80].

Many organizations other than those specializing in meteorology now possess radar sets. It is inevitable that reports will originate from some observers who are not properly trained in scope analysis. When these reach the forecaster he must weigh all the available data in deciding whether the reports are useful or misleading. Even with all available data he may find it difficult to decide whether an eccentricity in path as indicated by radar is real and possibly indicates a trend, or whether it is the effect of some of the many factors that complicate radar performance and scope interpretation. In addition there remains the question of the relation between the precipitation, pressure, and rotation centers which has not yet been clearly established. Frequently the distribution of observations from other than meteorological sources is not confined to the forecast offices. They may be passed to local weather offices not in possession of the complete data needed for proper evaluation, or on occasion, even be released to the public as confusing information conflicting with the official advisories. Procedures recently established for the collection of radar reports and their analysis and dissemination should help to solve some of the problems involved.

In addition to its use in tracking hurricanes, radar offers many other possibilities for hurricane observation. These include the distribution and intensity of the precipitation, the diameter of the eye, and indications of growth or decay. The great number of additional radar installations and studies of the results of observations and photographs within the next several years will unquestionably make this a much more important tool in hurricane forecasting.

MICROSEISMS

The term "microseisms" applies to all elastic wave systems which are propagated along the surface of the earth, but it does not include those caused by earthquakes or purely local, man-made disturbances. The type in which meteorologists are interested are called microseismic storms. These do not appear at all times, but in periods of hours or days, building up to a maximum and then dying down again [83]. Those produced by storms or fronts at sea, and in particular tropical storms, received considerable attention several years ago [38, 39]. These studies, which made use of networks established in both the Atlantic and Pacific, generally found that in certain situations and locations microseisms could serve to detect the presence of a tropical storm over ocean areas within the range of the observing station. With three stations receiving microseisms from the same storm its location and motion could be determined with some success. However, several factors have hindered the study and full use of microseisms for tropical storm detection. The relatively few microseismic stations established in tropical regions, plus the geological barriers which reflect and refract microseisms, have limited the area of surveillance. In addition proper interpretation of the data is often quite difficult.

Although the use of microseisms appeared promising on the basis of several storms found and tracked they needed additional "proving" with many more storms within the same and adjoining areas. During the last decade, however, particularly with the constant surveillance of hurricanes by reconnaissance aircraft, microseisms have been relegated to a minor experimental role in hurricane operations. Also whatever further evaluations of their usefulness have been made have not shown enough promise to warrant much additional research on their applicability to tropical storm detection.

SFERICS

Sferics is a contraction of the word atmospherics meaning natural electrical phenomena detected by radio methods. Sudden electrical discharges resulting in redistribution of charge within and between clouds, between clouds and the air space above or below, and between clouds and earth, give rise to electrostatic, induction, and radiation fields. The latter generally cause natural static which interferes with radio reception at a distance. The significance of sferics in meteorology is due to their origin in relatively intense convection involving water vapor. Sferics observations have taken several forms: determination of direction of arrival, measurement of intensity and rate of occurrence, and display of the wave form of individual sferics [158]. Day and night ranges of sferics at radio frequencies exceed, respectively, 1000 and 3000 miles.

By using several stations and triangulation procedures with data obtained by direction finders, sferics instruments provide the equivalent of an extremely dense network of observing stations within the working range. Sferics have been most useful over ocean areas in location of active polar fronts, wave cyclones, and thunderstorms. Studies relating to the utility of sferics in location of hurricanes have thus far tended to be inconclusive or negative. However, positive departures from normal in the disposition of sferics may yet be found in the neighborhood of developing tropical storms. Further work appears justified in view of reports from the western Pacific during World War II of their use in following easterly waves.

FORMATION AND INTENSIFICATION

CLIMATOLOGY

Formation

The overall annual and monthly frequencies of tropical storm formation in the North Atlantic area were covered earlier in this Guide. For the purpose of forecasting individual storm formation it is useful for the forecaster to know the climatological likelihood of a storm forming in a particular local section of the North Atlantic area. Such information was compiled a few years ago by Colón

[15] from the locations of initial points of published tropical cyclone tracks. These frequencies of formation have recently been revised by the Weather Bureau's Office of Climatology on the basis of a compilation of tropical cyclone tracks dating from 1887 through 1956 [110]. The average monthly frequencies of track origins (i.e. formation) for the months June-November are shown in figures 9 and 10.

There are essentially five main zones of tropical cyclone formation:

1. the Atlantic Ocean in the vicinity of the Lesser Antilles (mainly east of the Islands).
2. the western Caribbean Sea.
3. the Gulf of Mexico.
4. the Bahamas region.
5. the eastern Atlantic near the Cape Verde Islands.

In the month of September, when tropical storm activity is at its peak, there are pronounced concentrations in each of these areas. The Lesser Antilles zone is very active in August and September and in comparison with frequencies in other areas is the major zone of formation in both of these months. Weaker maxima are also present near the Lesser Antilles in July and October. The western Caribbean is the seat of maximum frequency of formation in June, but very few storms form there in July and August. Activity increases in this area in September and the peak of activity is reached in October when it leads all other zones. In November it is still the most active area of formation. Fairly well-marked maxima are located in the Gulf of Mexico and the Bahamas from July through October, while the Cape Verde area shows significant activity only in August and September.

It is interesting to note that there are large portions of the Atlantic region where formation of tropical cyclones is generally quite infrequent. Particularly notable is the eastern Caribbean which contrasts markedly with the high frequencies of formation near the Lesser Antilles and in the western Caribbean in most months.

Intensification

As yet there is relatively little detailed information on geographical and monthly variations in the intensification of tropical cyclones. Most of the information currently available deals with the transitions between one broad category of the tropical cyclone and another, specifically intensification from a tropical storm to a hurricane. The overall climatological likelihood of a tropical storm becoming a hurricane in its lifetime was discussed early in this Guide (e.g. 74 percent in August, 64 percent in September, 46 percent in October in the North Atlantic area). A recent study by Dunn [26] shows the locations where tropical cyclones have reached hurricane intensity in the various months. The charts for the three peak hurricane months, August through October, revised to include 1957, are shown in figures 11-13. In cases in which a disturbance intensifies very suddenly to hurricane strength, the indicated locations may also be the places of formation, but for the most part these systems traveled for some time as depressions and storms before becoming hurricanes. Nevertheless there are some overall similarities between the regions of frequent tropical cyclone formation (figs. 9 and 10) and the areas of hurricane development, which suggests that both formation and intensification very likely result from the operation of similar physical processes.

A few statistics on the development of hurricanes of extreme intensity (i.e., maximum winds in excess of 150 kt) were recently presented by Project AROWA [153]. For a limited sample of years (1952-1955 in the Pacific and 1950-1955 in the Atlantic) there were 25 storms (typhoons and hurricanes) which exhibited wind speeds in excess of 150 kt. These storms reached this extreme intensity in the various latitude belts with the following frequencies:

10° - 15°N	7
15° - 20°N	12
20° - 25°N	5
north of 25°N	1.

These data seem to indicate that this type of very intense hurricane will rarely develop north of latitude 25°N. Any conclusions or comparisons using these data must be extremely tentative, however, since the sample is very small and both Pacific and Atlantic areas have been thrown together.

INFLUENCE OF LONG-PERIOD CIRCULATION ANOMALIES

It was demonstrated earlier in this Guide that the frequencies of Atlantic hurricanes undergo marked fluctuations from year to year. It is generally assumed that these fluctuations in hurricane frequency must have some basic relationships to year-to-year differences in the prevailing states of the large-scale circulation, at least over the Atlantic area. Namias [104] has pointed out that longer-period average flow patterns (30-day and 5-day) can be used to locate areas favorable and unfavorable to tropical storm formation. In a study of the relationship between the large-scale circulation and seasonal frequencies of North Atlantic tropical storms, Ballenzweig [4] has shown that there are well-marked differences between seasonal circulation patterns in years of frequent tropical cyclone activity as contrasted with years of infrequent occurrence. Charts of the average 700-

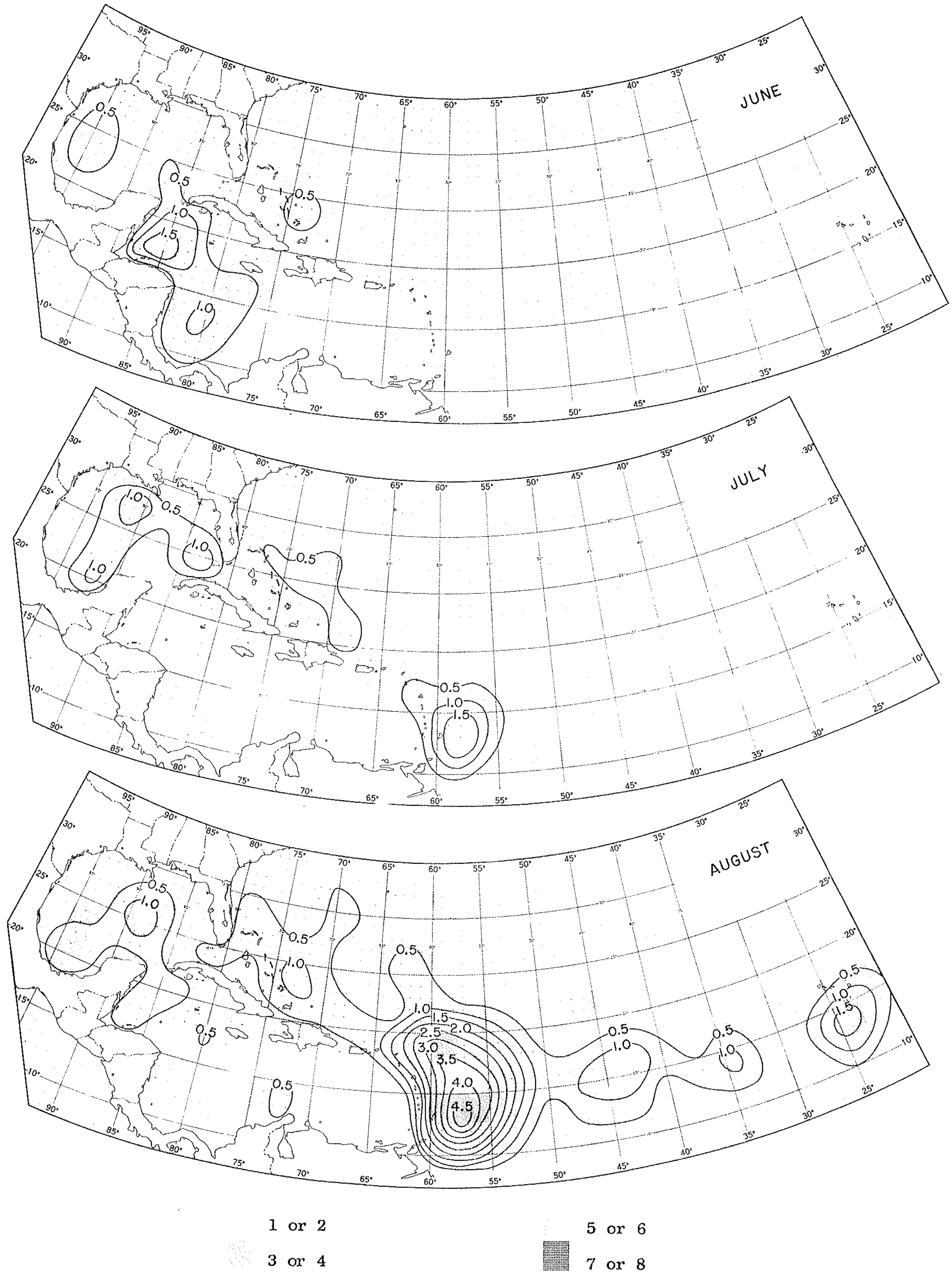


Figure 9. - Geographical frequencies of tropical storm formation (track origins) by $2\frac{1}{2}$ deg lat-long areas, 1887-1956 for months June-August. Isopleths are drawn for frequencies space-averaged over 4 adjacent $2\frac{1}{2}$ deg areas (adjusted in coastal regions). (After Office of Climatology [110])

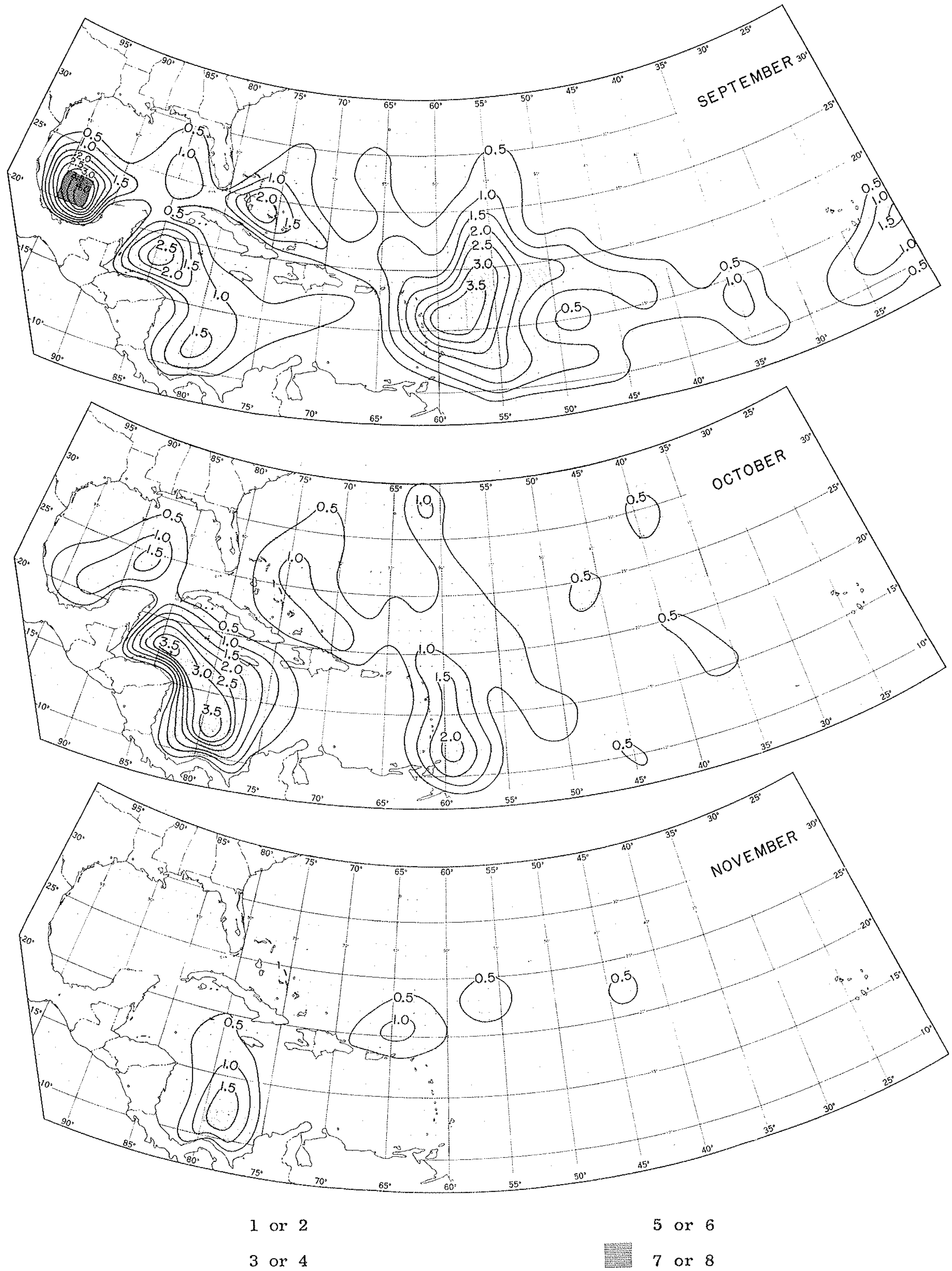


Figure 10. - Geographical frequencies of tropical storm formation (track origins) by $2\frac{1}{2}$ deg lat-long areas, 1887-1956 for months September-November. See legend to figure 9. (After Office of Climatology [110])

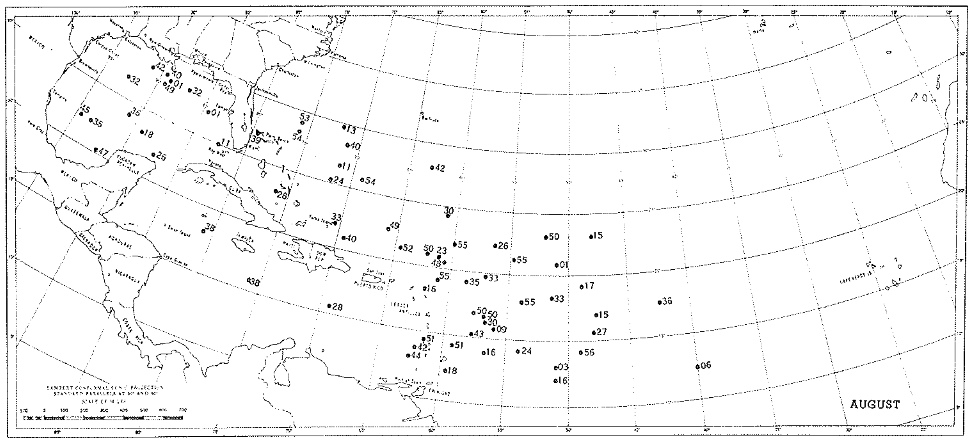


Figure 11. - Locations where tropical storms reached hurricane intensity, August 1901-1957. The two-digit number at each location indicates the year.

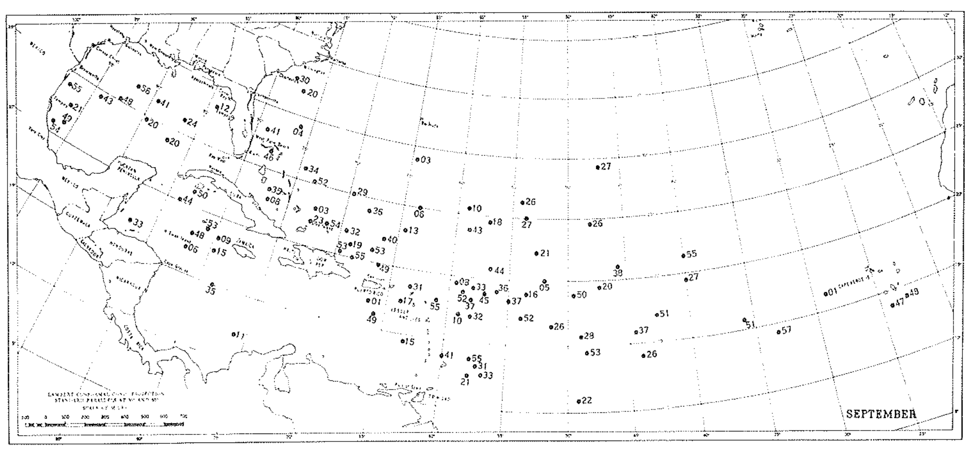


Figure 12. - Locations where tropical storms reached hurricane intensity, September 1901-1957. The two-digit number at each location indicates the year.

mb height anomalies for those 5 seasons (August-October, in the period 1933-1955) with maximum tropical cyclone formation in the entire Atlantic region and the average height anomaly for those five seasons with minimum formation are shown in figures 14 and 15, respectively.

The anomaly patterns for maximum and minimum storm occurrence differ considerably over the Atlantic area. In the years of maximum frequency positive anomalies are extensive across the entire Atlantic near latitude 40°N while negative anomalies prevail near Iceland and in subtropical portions of the Atlantic and Caribbean. In years of minimum frequency there is also an area of positive anomaly in the Atlantic, but it is located closer to latitude 30°, while an elongated negative anomaly area stretches eastward from the Great Lakes region to the central Atlantic and

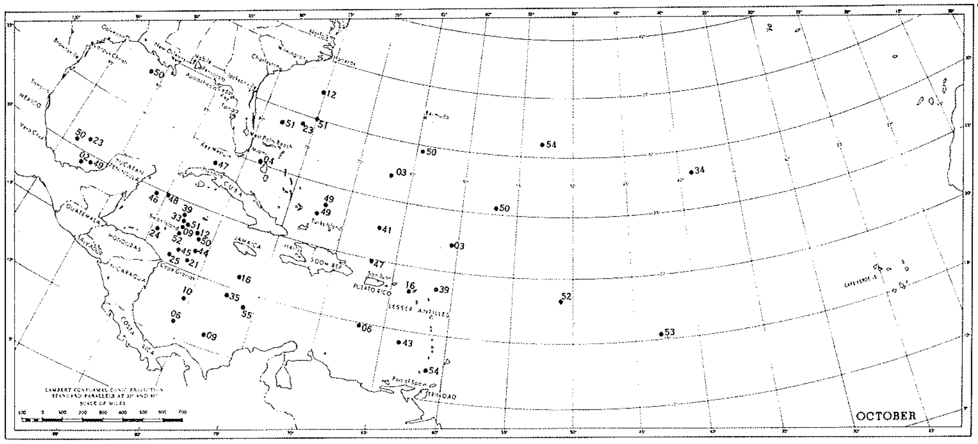


Figure 13. - Locations where tropical storms reached hurricane intensity, October 1901-1957. The two-digit number at each location indicates the year.

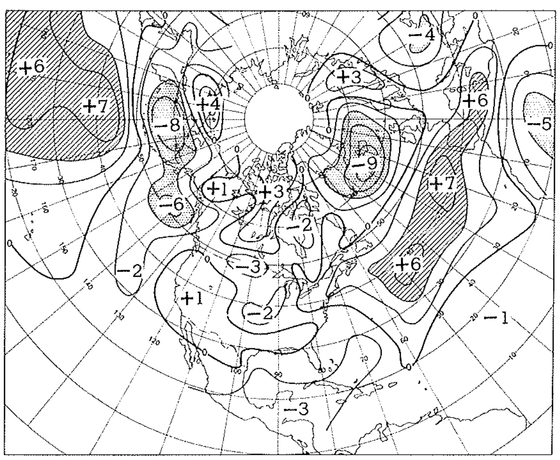


Figure 14. - Average departures from normal (in tens of feet) of 700-mb heights for the 5 seasons (August-October) of maximum tropical cyclone incidence in the North Atlantic area. (After Ballenzweig [4])

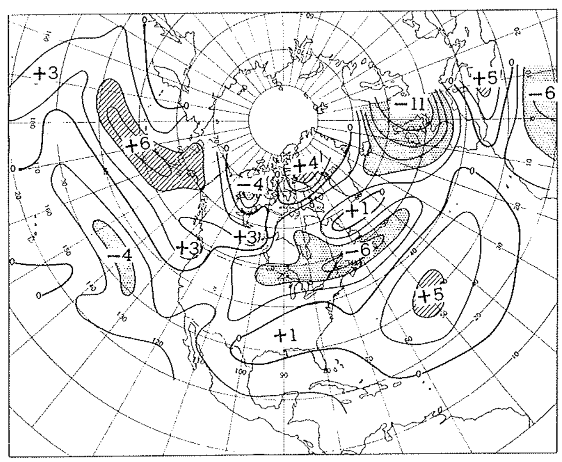


Figure 15. - Average departures from normal (in tens of feet) of 700-mb heights for the 5 seasons of minimum tropical cyclone incidence in the North Atlantic area. (After Ballenzweig [4])

negative anomalies prevail near the British Isles. These differences essentially reflect the fact that the westerlies, the subtropical ridge, and the subtropical easterlies over the Atlantic are farther north in years of maximum tropical storm formation and farther south in years of minimum tropical storm formation. This picture generally confirms in a broad-scale sense the findings of Riehl [123] that tropical storm development is related to the strength and position of the upper-level westerlies over the middle latitudes. Also this is what one would expect from the normal seasonal relationship of tropical storm activity to the latitude of the westerlies, i.e., the greatest number of tropical cyclones occur near the time of the year when the westerlies are at their highest latitude. Thus, broadly speaking, anomalous flow patterns which accentuate the seasonally favorable pattern result in the formation of more tropical cyclones than normal in the Atlantic, while anomalous flow patterns which are more akin to seasonally unfavorable (colder season) patterns result in fewer tropical cyclones than normal.

These relationships serve to highlight the

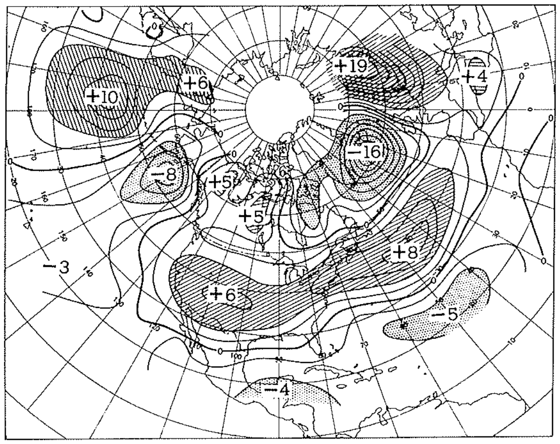


Figure 16. - Average departures from normal (in tens of feet) of 700-mb height for the 8 months during which at least two tropical storms developed in the eastern Atlantic. (After Ballenzweig [3].)

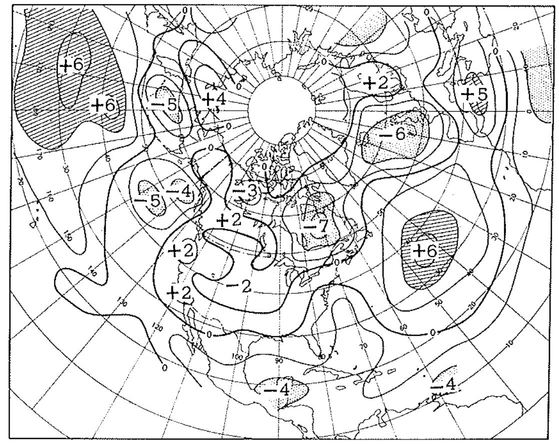


Figure 18. - Average departures from normal (in tens of feet) of 700-mb height for the 14 months when at least two tropical storms developed in the vicinity of the Lesser Antilles. (After Ballenzweig [3].)

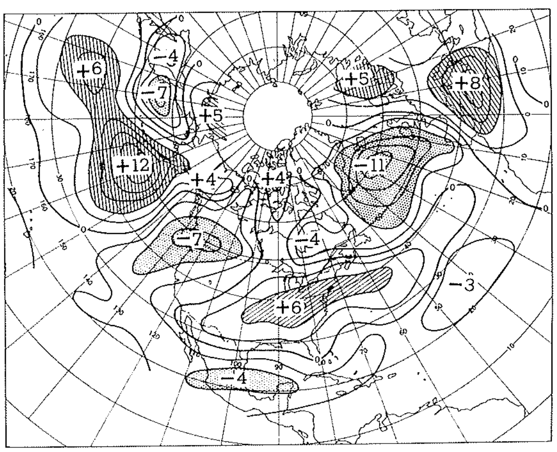


Figure 17. - Average departures from normal (in tens of feet) of 700-mb height for the 7 months during which at least two tropical storms developed in the Gulf of Mexico. (After Ballenzweig [3].)

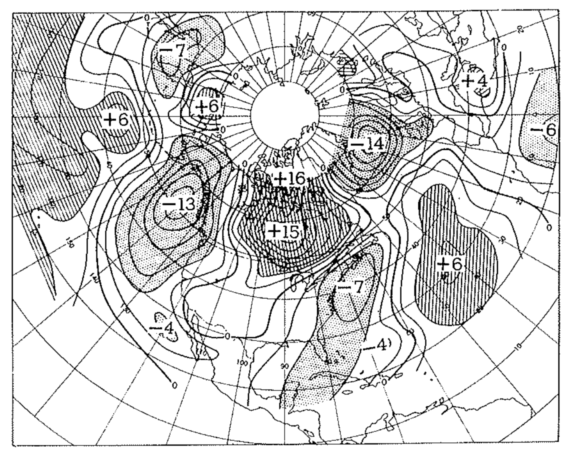


Figure 19. - Average departures from normal (in tens of feet) of 700-mb height for 8 months when at least two tropical storms developed in the Caribbean. (After Ballenzweig [3].)

seasonal circulation features associated with high and low frequencies of storm formation in the Atlantic. They would, of course, prove of most practical value if methods of predicting seasonal circulation patterns, even in a very gross sense, could be developed. Up to the present time skillful seasonal predictions are far from a reality. Some success has been achieved, however, in making 30-day outlooks [103], which have constituted a regular semi-monthly product of the Weather Bureau for some time. Further investigation by Ballenzweig has shown that the circulation patterns associated with high and low frequencies of tropical storm formation for monthly periods are basically similar to the seasonal patterns, which indicate that the seasons included in figures 14 and 15 were generally homogeneous in regard to major circulation anomalies. Thus, these composite seasonal circulation patterns can be used as guides in making monthly predictions of the frequency of tropical storm formation, once the circulation prognosis has been made.

Although a general forecast of the overall frequency of tropical storm activity in the Atlantic is valuable, it is of more importance to specify more precisely which portion(s) of the Atlantic will be the preferred site(s) of storm formation during the next month. Ballenzweig [3] has demonstrated that there are generally some rather well-defined circulation features which accompany storm formation in particular areas of the Atlantic and some of these are illustrated in figures 16-19. These charts are averages of monthly mean 700-mb height anomalies for those Augusts, Septembers, and Octobers between 1933 and 1955 when two or more tropical storms formed in various areas of the Atlantic. (The exact boundaries of these areas are outlined in figure 38.) Of course, such a study is subject to the possible errors arising from the occasional uncertainty as to whether a storm actually formed in the area where it was first detected. Also, classification of storms on the basis of formation in certain small areas in a given month may result in excessive subdivision of the data. After all, the appearance of two storms in a month hardly indicates conclusively that the given area is a preferred site for formation, yet the cases with any more than two per month in the areas chosen are quite rare. Despite these apparent restrictions these charts contain some rather clear-cut anomaly fields which seem physically reasonable.

Figures 16-19, as might be expected, have several common characteristics which generally bear some resemblance to the composite chart for seasons of maximum hurricane frequency in the entire Atlantic (fig. 14). Particularly notable are the height anomalies in the Atlantic area, where negative anomalies generally prevail near Iceland and in subtropical portions of the Atlantic, Gulf, and Caribbean, while positive anomalies prevail near latitudes 35° - 40°N.

However, the composites for the various areas of formation have several distinctive characteristics of their own. For the most part the strongest negative height anomalies in the subtropics prevail over the areas of formation, which generally reflects the tendency for tropical storms to form in regions where 700-mb flow is more cyclonic than normal. It is interesting that the charts for formation in the Atlantic east of the Antilles (fig. 16) and in the Gulf of Mexico (fig. 17) both display a broad zone of easterly flow relative to normal across the Atlantic and southern United States. However, positive anomalies are considerably stronger in the Atlantic in the former case while they are weaker in the Atlantic and stronger over the eastern United States in the latter case. Meanwhile storms forming in the Lesser Antilles (fig. 18), the western and central Caribbean (fig. 19), and the Atlantic north of the Antilles (not shown) are not accompanied by extensive easterlies with respect to normal, but mainly exhibit some northward extension of negative anomalies near the east coast of the United States. This is probably associated with the fact that many of the cyclones forming in these areas move northward in a mean trough near the east coast of the United States and, also, that many of these storms form at or near the intersections between the intertropical convergence zone and the southern ends of polar troughs which reach far southward into the Tropics near the east coast. This latter situation probably occurs most frequently in the case of Caribbean storms (fig. 19), the majority of which form during October when polar troughs have more opportunity to extend into the deep subtropics. This group also exhibits the strongest anomaly pattern of all the composites over Canada, where positive anomalies are large in magnitude and extent. The significance of these positive anomalies relative to storm formation probably lies in their action in depressing the westerlies in eastern North America so that the trough off the east coast of the United States is quite deep at middle and lower latitudes. All of these charts (figs. 16-19) also have well-defined centers of positive and negative anomalies in various portions of western North America and the Pacific. These are somewhat remote to be connected directly with tropical cyclone formation in the Atlantic, but they are probably of importance in supporting the anomalous circulation patterns over central and eastern North America and the Atlantic.

These patterns favorable to tropical storm development essentially suggest that at least one of the mechanisms proposed by Namias [104] may be operating to induce storm formation. The items he suggests are: cooler than normal temperatures in mid-troposphere, so that vertical instability over warm oceans would be pronounced; and transport of a broad field of cyclonic vorticity into the Tropics. The presence of negative anomalies on monthly mean composite charts in the areas of formation suggests that cyclonic vorticity and below-normal temperatures are prevalent at 700 mb during the months when storms form. Also, Namias points out that a northward shift of the westerlies generally is associated with more frequent shearing of southern portions of polar troughs from their progressive northern sections, and hence provides a mechanism for maintaining cold air and cyclonic vorticity in the Tropics after transportation from northerly latitudes. The foregoing charts indicate that the westerlies are indeed north of normal over the Atlantic for cases of maximum frequency of tropical cyclone occurrence in the entire area (fig. 14) and also in most cases favorable for occurrences in particular areas (figs. 16-19).

These considerations indicate that general prediction of areas favorable or unfavorable for hurricane formation are feasible for monthly or shorter periods (similar large-scale, circulation relationships generally exist for 5-day mean charts), providing the circulation patterns can be predicted with a fair degree of skill. However, the problem of determining precisely when and where a tropical cyclone will form in a 5-day forecast period (or even in 24 hr for that matter) is of a higher order of difficulty and is presently done on a very subjective basis. Many of the considerations treated in the following section are also used in 5-day prognostication of hurricane formation.

SHORT-RANGE PREDICTION OF TROPICAL CYCLOGENESIS

Basic Aspects of Tropical Cyclogenesis

The basic elements necessary for generation and intensification of a tropical storm are treated in a systematic fashion by Riehl (cf., pp. 326-339 of [125]). His analogy of tropical storm generation to the operation of a machine provides a very clear conception of the various elements which must operate to produce a hurricane. Briefly summarized, the kinetic energy of the hurricane is derived from conversion of heat energy released in condensation of moisture in tropical air which is lifted over a large area. The most important aspects of the problem from the point of view of predicting formation and development of the hurricane are the necessity for an adequate supply of latent heat and a mechanism for starting and maintaining the upward motion which produces condensation. The latter requires a strong low-level inflow of air (associated with increases in the surface pressure gradient) and a slightly overcompensating outflow at higher levels. At present the forecaster is forced to subjectively evaluate the possibilities of the proper development of such circulation features. It is anticipated that future improvements in dynamical prediction models, which will take proper account of the thermodynamic elements associated with tropical cyclones, will gradually lead to satisfactory objective means for predicting formation and deepening of the tropical cyclone.

Synoptic Flow Patterns

It has been generally observed that tropical storms form only within pre-existing cyclonic disturbances found in easterly waves, in the intertropical convergence zone, and in the trailing southerly portions of old polar troughs. In the Atlantic area the easterly wave is the most prolific producer of tropical storms. For example, Dunn [26] points out that about 80 percent of the storms which developed to hurricane strength in the Atlantic between 1901 and 1955 originated in easterly waves, while about 15 percent developed in the intertropical convergence zone. Generally, the vast majority of these low-level cyclonic disturbances do not develop into tropical storms or hurricanes unless there are some triggering mechanisms which concentrate convergence and cyclonic vorticity in the lower and middle troposphere and divergence in the higher troposphere.

Easterly Waves - The importance of the easterly wave in tropical storm forecasting was first recognized by Dunn [24] who observed a series of isallobaric centers moving from east to west across the islands in the Caribbean. When upper-air observations later became more numerous, these centers were found to be associated with the westward progress of definite wind shifts and hence were symptomatic of wave propagation. The isallobaric pattern, however, still remains one of the most useful tools in following the motion of the waves.

The exact origin of all easterly waves is difficult to trace. Many apparently originate in the easterlies, whereas others have been definitely traced back to the fracturing southern ends of troughs in the middle-latitude westerlies. For example, of 29 easterly waves in the Atlantic in 1944, Cressman [19] noted that 10 originated as fractured westerly troughs, while the remaining waves moved into the region of observation from the east. The manner in which an easterly trough may develop from an extended westerly trough is illustrated in figure 20. The shearing or fracturing of the southern end of the trough, which becomes the easterly wave, is favored when the westerlies flatten in middle latitudes (i.e., the westerly trough weakens) and/or the trough moves eastward at speeds more than about 4 deg lat/day. Cressman [19] has presented some quantitative statistical criteria which can be used to estimate the likelihood of this trough fracture based on the two basic considerations just mentioned.

Figure 21 shows Riehl's conception of the idealized stable easterly wave. This type of wave is essentially a cold core phenomenon, sloping eastward with height. The cold air is dynamic rather than advective in origin. Subsidence and divergence precede the wave, the pressure falls, the trade wind inversion lowers, and little or no cloudiness is observed. As the wave approaches, the height of the moist layer rises and towering cumulus begin to develop. Behind the wave, convergence and ascent occur, the pressure begins to rise, heavy cumulus and cumulonimbus become numerous, and middle and high cloudiness develop as the moist air extends to high levels. Convergence with associated shower and thundershower activity reach a maximum at about 200-300 mi behind the surface trough. A wave in the easterlies is present over some part of the Caribbean almost every day from June through September, with a somewhat lesser frequency in May, October, and November. A station in the eastern Caribbean may

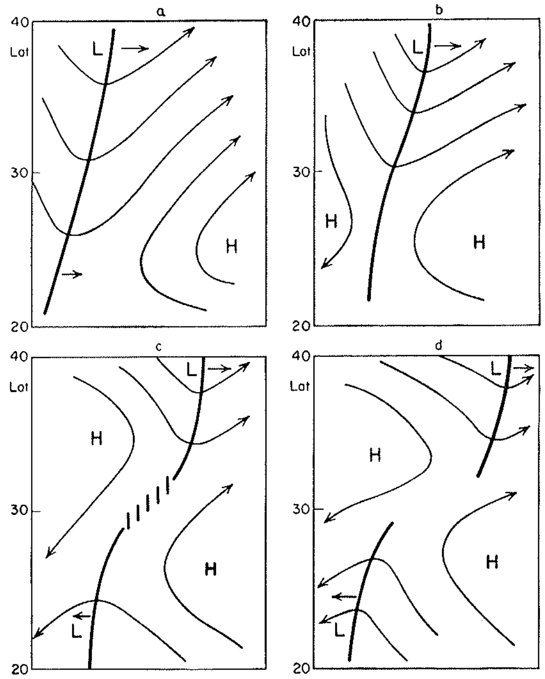


Figure 20. - Four stages during development of trough in easterlies formed by splitting of poleward and equatorward parts of extended westerly trough. (After Riehl [125]; by permission of University of Chicago, Copyright 1945.)

expect a wave passage on the average about twice a week. Most of these waves are stable, with perhaps every third or fourth wave showing signs of becoming unstable.

The unstable easterly wave exhibits a marked increase in amplitude and may develop sufficiently to transform into a tropical cyclone. In the unstable wave strong convective activity and squalliness occur along and to the west of the wave, as well as to the east as in the case of the stable wave. Showers and thundershowers may extend as much as 300-400 mi ahead of the surface position, with an abundance of cloudiness at all elevations. The observed development of an unstable easterly wave with attendant pressure falls serves to alert the forecaster to the increased likelihood of tropical storm development. In addition, however, there are several other features of synoptic charts that have been found to give some indications of deepening of easterly waves. Some of the following features have an obvious physical basis, while others are largely empirical.

In general, the basic character of the upper flow pattern is vitally important to intensification of the easterly wave. Riehl [123] describes two classes of westerly currents over the subtropical

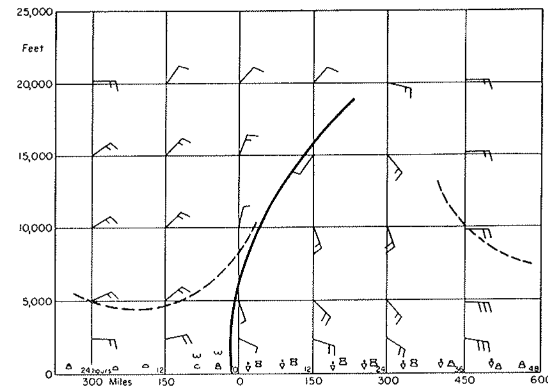


Figure 21. - Model of an easterly wave in vertical section. Dashed line shows depth of moist layer. (After Riehl [125]; by permission of University of Chicago, Copyright 1945.)

area: 1. Those connected with a baroclinic westerly current, in which the west wind increases with height and the base of the westerlies slopes gradually upward toward lower latitudes. This situation is very unfavorable for tropical storm formation. 2. Those connected with a quasi-barotropic westerly current, in which the west wind remains almost constant with height and the slope of the base of the westerlies tends toward the vertical. This type of flow, where the upper westerlies over the subtropics are weak, favors an increase in the amplitude and intensity of tropical perturbations and the formation of tropical storms.

Intensification of easterly waves frequently occurs as a result of superposition of a trough in the westerlies and a wave in the easterlies as they approach each other longitudinally [19]. The increasing meridional wind components associated with superposition generally result in falling pressures in the wave. If a closed cyclonic circulation develops in the wave it usually does not fill even after the easterly and westerly waves separate.

Another clue to easterly wave intensification may be found in the strengthening of the subtropical high cell. For example, Norton [109] suggested that high pressure areas from the temperate latitudes moving out into the Atlantic and reinforcing the semi-permanent Bermuda-Azores-Atlantic cell produce a line of cyclonic wind shear or surge in velocity in the trade wind belt, either at the surface or aloft, or both. When such a surge or increased concentration of cyclonic vorticity comes into contact with an easterly wave, it may be changed quickly from a stable wave into a tropical cyclone. Such buildups of the Atlantic high probably occur mainly as the result of developments in the westerly wave pattern in middle latitudes. This effect of pressure rises in the oceanic anticyclone has also been emphasized by Riehl [123].

Experience has shown that warming at intermediate levels north or east of any wave that slopes to the west may be regarded as potentially dangerous. This warming indicates that the vertical circulation (fig. 22) postulated by Riehl [125] is operating efficiently and that enough heat of condensation is being transported upward to transform the cold core wave into a warm vortex. Hubert [54] pointed out that this warming can result only from large-scale ascent of air initially at the surface.

Formation of closed lows in easterly waves usually occurs at the point of maximum cyclonic shear in the easterlies. Frequently two or more minor centers form on an unstable wave. Usually the northernmost center develops at the expense of the others, probably due at least partially to the slightly greater Coriolis parameter at the more northerly point.

Various attempts have been made by Riehl [125], Palmer [113], and others to relate the stability of a wave to its slope, to its speed relative to the basic easterly current, and to the vertical wind shear above the wave, but these have not proved to be of much use in actual forecasting practice.

<u>The Intertropical Convergence Zone</u> - In the Pacific area many typhoons form in the Intertropical Convergence Zone (ITC). Such is not the case in the Atlantic area, mainly due to the presence of the large South American land mass across much of the normal summertime position of the Intertropical Convergence Zone. The ITC is located farther north in the vicinity of the Cape Verde Islands and in the southwestern Caribbean Sea, near Central America, and these are the only regions where hurricanes normally form along the surface position of the ITC.

In the Pacific, the intersection of a shear line with the crest of a perturbation on the intertropical convergence zone in what Deppermann [23] calls the "triple point" is a prolific producer of tropical storms. In the Atlantic, however, shear lines seldom retain their identity far enough south to intersect the ITC, which accounts for the fact that storms in the Atlantic can seldom be traced back to a "triple point" origin.

<u>Polar Troughs</u> - Polar troughs play several important roles in tropical cyclone development. The influence of the polar trough on the development of a vortex within the equatorial shearline and the fact that the superposition of a polar trough and an easterly wave can cause both to deepen have already been mentioned. In addition, trailing, stationary, or fractured portions of old polar troughs may provide the initial concentration of cyclonic vorticity necessary for hurricane formation. This occurs mainly in the Gulf of Mexico, the Caribbean, and in the Atlantic between the Bahamas and Bermuda.

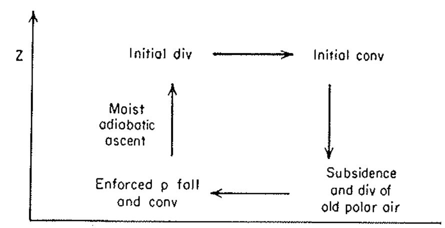


Figure 22. - Model of vertical cross-stream circulation in a tropical storm. (After Riehl [125].)

<u>Upper-Tropospheric Systems</u> - Experience with analysis of high-level charts (e.g., 200 mb) during hurricane situations in recent years has permitted some tentative identification of certain circulation patterns that seem to be favorable for the development and intensification of tropical cyclones. Basically, of course, the flow above the storm at these higher levels must provide the necessary outflow or divergence which allows for the low-level pressure falls of the intensifying storm. This outflow circulation must carry the excess heat generated by condensation some distance from the storm area; for, if it is not carried away, but descends too near the storm, the resultant warming would have a damping effect on the storm [153]. Thus it is logical to expect that those situations in which a markedly divergent flow at high levels is vertically superimposed on a low-level cyclonic disturbance would be most favorable for hurricane development.

Before proceeding to some of the findings directly related to cyclonic development, it is worth discussing briefly the general nature of high-level flow in the Tropics in the hurricane season, which was recently summarized by Riehl ([125], pp. 243-256). A frequent feature of high-level charts in the vicinity of latitudes 15° - 25°N is an east-west cyclonic shear zone which may be associated with a northward tilt of the Intertropical Convergence Zone, which is found farther south at the surface. This high-level trough is a cold-core feature while the associated low-level trough has a warm core. An example of this type of high-level shear line is shown in figure 23.

Perhaps the most characteristic features of high-level flow in the Tropics in the hurricane season are the series of cyclonic and anticyclonic vortices which generally move from east to west.

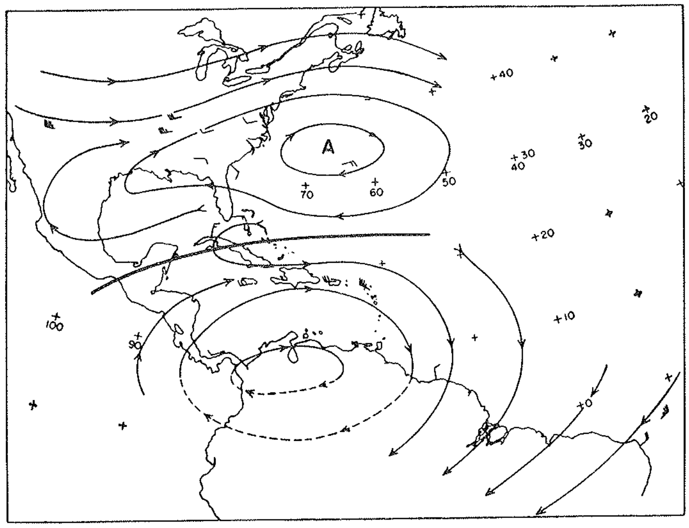


Figure 23. - Equatorial shear line at 30,000 ft, Sept. 27, 1945. (After Riehl [123]; by permission of University of Chicago, Copyright 1948.)

Riehl [124] and Palmer [114] made some of the pioneering studies of the origin and behavior of these systems. Unfortunately the usual sparsity of data in the tropical oceans has thwarted all but a few detailed investigations of these high-level vortices. However, with the aid of a relatively good observational network in the Pacific during 1945, Riehl [124] was able to make some rather thorough studies. In one typical case (September 1945) he found that high-level vortices were centered near 20°N, had a north-south extent of roughly 20 deg lat, and had an average spacing of 45 deg long between cyclone centers. During the period of his study, the upper vortices had an average displacement westward of $6\frac{1}{2}$ deg long/day, which was very nearly equal to the average speed of the easterlies. Thus during an average week a station should experience the passage of one upper vortex.

Riehl made the interesting observation that the high-level vortices in the Tropics have about the same spacing as the long waves in the temperate-latitude westerlies, whereas the easterly waves in low levels are basically similar to the short cyclone waves of middle latitudes. Assuming these analogies generally hold, it is easy to see that the high-level tropical vortices may have interactions with low-level easterly waves or other low-level vortices which are grossly similar to the relationships between long waves and cyclone waves. Thus, with proper superposition of high-level divergence associated with a certain part of the upper-vortex train and convergence in the low-level disturbance, marked intensification of the latter will result. The most likely upper-flow situations associated with divergence are those where the flow is already anticyclonic or is becoming more anticyclonic through the advection of more anticyclonic vorticity. A schematic illustration by Riehl [125] of such a favorable pattern is shown in figure 24. However, recent case studies of intensification reveal somewhat more varied upper-level flow patterns associated with intensifying storms.

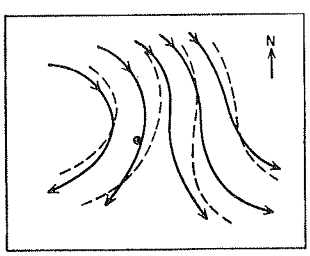


Figure 24. - Northerly high-level current favorable for cyclonic development of low-level tropical disturbance (indicated by dot). Solid lines are streamlines and dashed lines are 200-mb contours. (After Riehl [125].)

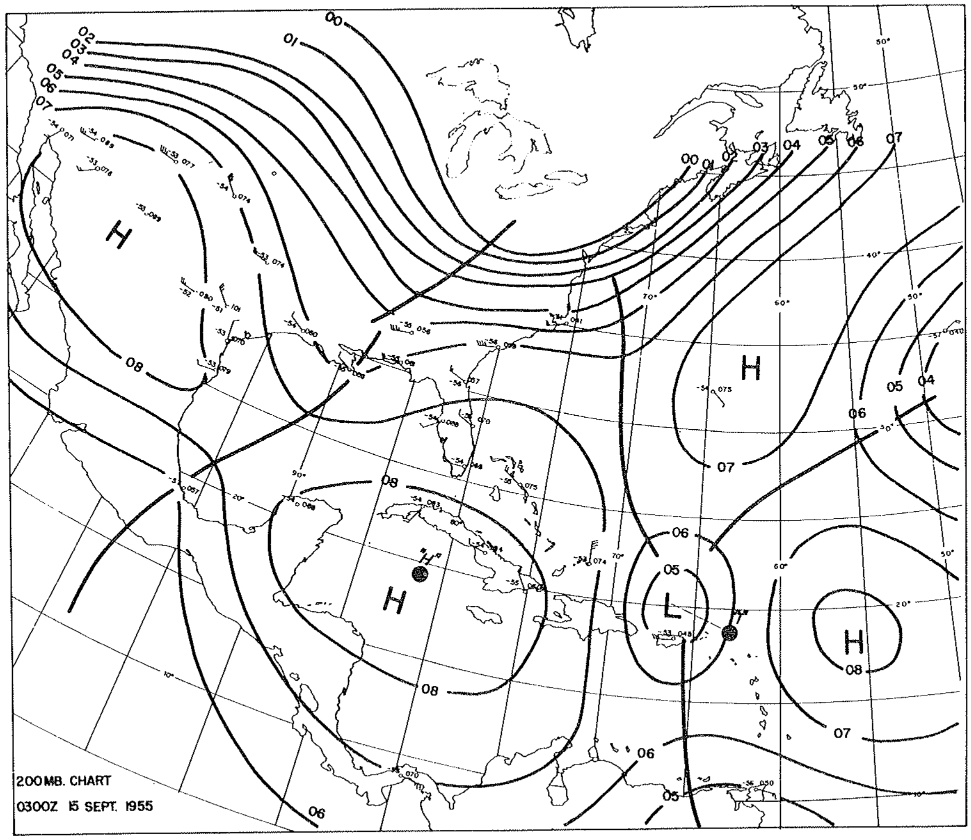


Figure 25. - 200-mb chart for 0300 GMT, Sept. 15, 1955 showing high-level flow in relation to surface positions of hurricanes "H" and "I" (indicated by large dots). (After U. S. Navy [153].)

One case recently studied by Project AROWA [153] is illustrated in figure 25. Note that hurricane Hilda ("H"), which was located south of Cuba moving on a westward track and was still quite weak, was located under the center of an anticyclone at 200 mb. This is a favorable circulation for outflow which in this case could spread over a wide area and deepening of this hurricane would be predicted. This storm did indeed undergo rapid deepening as it approached Yucatan during the following 24 hr. On the other hand, the high-level flow associated with hurricane Ione ("I" in fig. 25) at this time was very different. It is essentially a convergent flow pattern which should prevent rapid deepening of the storm. During the next day Ione actually maintained a relatively constant central pressure.

Some further study of the 200-mb circulation for the period between two days prior to and one day following the maximum intensities of hurricanes has been made by Miller [85]. He constructed two sets of composite charts, one set for five major (intense) hurricanes and the other set for four minor (weak, with little deepening) hurricanes. These composites, which are shown in figures 26 and 27, do not agree too well with the observations mentioned previously, since an average 200-mb cyclonic center appears over the deepening storms, while the storms with little deepening actually appear more divergent right

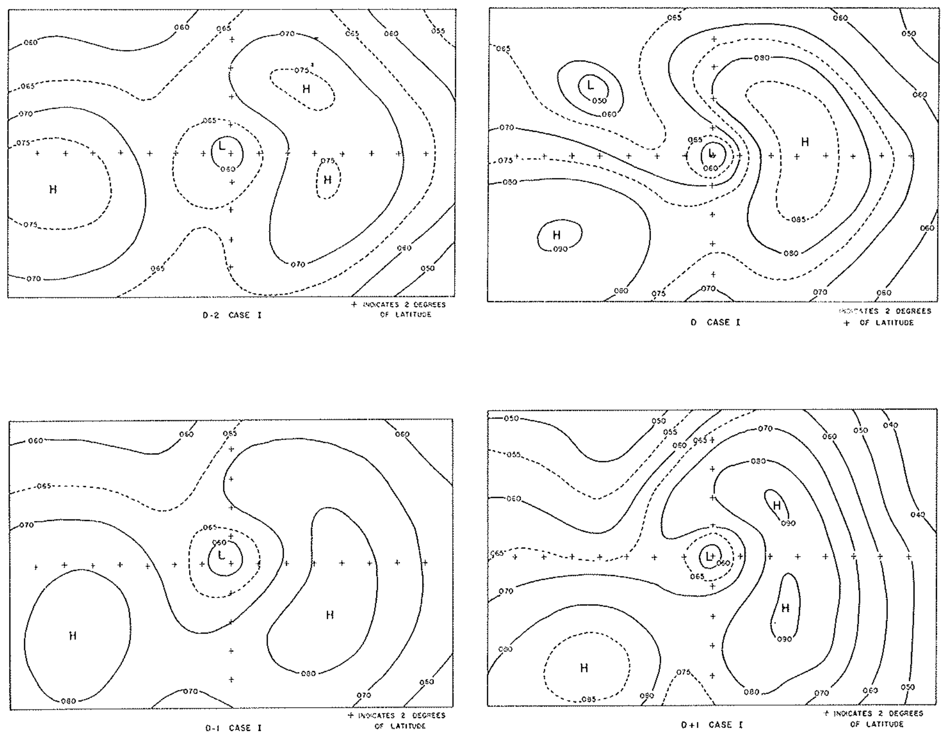


Figure 26. - Composite 200-mb charts of five major hurricanes. Storm center is located at intersection of horizontal and vertical axes. D day is the day the lowest pressure was observed. (After Miller [85].)

over the center. Miller's interpretation of these results does not mention this discrepancy, but rather emphasizes the broader-scale features surrounding the storms as influencing the outflow. For the deepening storms (fig. 26) he believes that the combined pattern of an anticyclone to the east and a trough to the northwest serves as an efficient outflow mechanism for the air lifted to this level around the hurricane center. On the other hand he interprets the pattern in figure 27 as being less divergent.

From these various findings it appears that there are as yet no uniform flow models for the 200-mb level which can be interpreted at sight as favoring deepening or filling of a hurricane. This is probably due to the fact that at low latitudes it is difficult to estimate divergence patterns from the contour field; good observed wind data are needed to make a quantitative appraisal of divergence. Furthermore, another cause for these varying results may lie in the fact that the major level of outflow probably varies with each hurricane. Particularly in intense hurricanes one may have to look to a higher level such as 100 mb for the strong high-level divergence necessary for intensification or even maintenance of the circulation. It is hoped that observational data will be more numerous and more accurate in the next several years so that more definite knowledge of the influence of the high-level circulation on tropical cyclogenesis will be obtained.

Vertical Instability

Although the simple convectional theory of hurricane formation is no longer accepted today, the role that convection plays in the process is undeniable. Widespread convection always accompanies the early stages of hurricane development and is a necessary part of the process, but convection alone, however intense, is not sufficient. Organized convection must take place within an

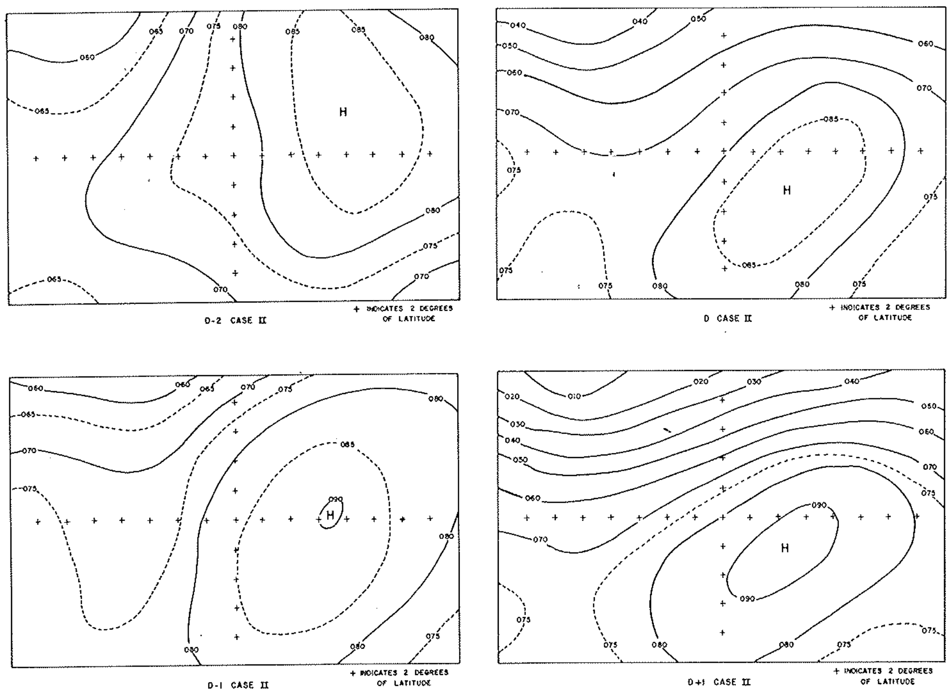


Figure 27. - Composite 200-mb charts of four minor hurricanes. Storm center is located at intersection of horizontal and vertical axes. D day is the day the lowest pressure was observed. (After Miller [85].)

existing low-level disturbance, which in turn must be favorably located in relation to circulation and thermodynamic features of the upper atmosphere.

Vertical instability may be created by warming at lower levels, cooling at upper levels, or by the addition of moisture in the lower layers. These may be produced by one or all of the following processes:

Differential Advection - Warm air advection at lower levels and/or cold air advection aloft act to create instability. In the Tropics, low-level warm advection is probably unimportant since tropical air is relatively homogeneous. Cold air advection at middle and higher levels of the troposphere, however, is likely to occur and may possibly contribute to destabilization in some cases.

Upward Motion - Large-scale upward motion associated with convergence in the lower levels and divergence aloft can cause considerable cooling aloft and general destabilization of the lapse rate over large regions. Of course, this type of cooling aloft is characteristic of cold core disturbances and not the warmth of the hurricane rain area [125]. However, we are concerned with tropical cyclogenesis at this point, and as discussed in the preceding section, tropical storms usually form in pre-existing cyclonic tropical circulations which are primarily of the cold core type. The warmth of the hurricane aloft has been explained best in terms of parcel thermodynamics, e. g., Byers [12] has aptly compared the hurricane to a huge parcel of air. The only way the "huge parcel" can be lifted to high levels by buoyancy is if the environment is sufficiently cool aloft relative to the equivalent potential temperature of the "parcel" near the surface.

Surface Heat and Moisture Sources - The tropical oceans supply both heat and moisture to the lower levels of the air, which increase instability of the air, both real and latent. The fact that hurricanes almost always form over tropical waters during the warm season of the year points to the obvious conclusion that sea-surface temperatures play an important role in the mechanics of formation.

Palmén [112], for example, showed that in the

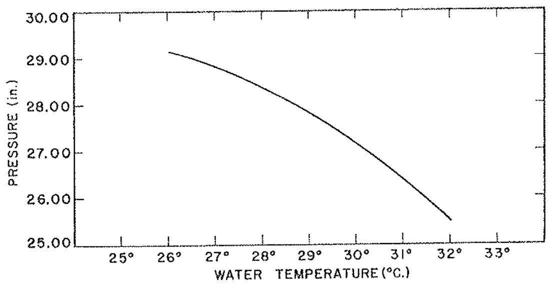


Figure 28. - Minimum probable pressure within a hurricane over various sea-surface temperatures. (After Miller [85].)

mean if the surface air at Swan Island were lifted, it would be much warmer than the mean sounding for September up to about 160 mb, while in February the lifted air would be about the same temperature as the surrounding air. This means that there is sufficient instability for possible tropical storm formation in September but not in February, which agrees with the seasonal variation of hurricane formation in the western Caribbean. From this consideration and also from the observed climatology of hurricanes Palmén concludes that tropical storms will not form over waters having surface temperatures less than about 80°F. This limit seems to be rather critical since there have indeed been rather few observed cases of fully developed hurricanes in tropical oceanic regions where the normal water temperature is less than 80°F.

Obviously variations from Palmén's normal pattern of instability would result from anomalies of both sea-surface and upper-air temperatures which exist at the time of actual or potential storm formation. A recent study by Fisher [28] of synoptic sea-surface temperatures associated with the formation and subsequent movement of several hurricanes in the period 1953-1955 shows that all storms where data were available formed where water temperatures were about 83°F or higher. On the other hand there have been cases where sea-surface temperatures were definitely below 80°F. One example of this was hurricane Alice of January 1955, a rare winter storm in the Atlantic area. Colón [16] found that the water temperatures were somewhat less than 77°F during this storm's development. Another example is the hurricane of May 1951 discussed by Moore and Davis [94], which formed off the Florida coast where sea-surface temperatures were well below 80°F. Their investigation of upper levels showed a cold pool aloft above the hurricane, e.g., 300-mb temperatures were as much as 7°C below normal.

If sea-surface temperatures are of consequence in the formation of tropical cyclones, they should also have some influence on the intensification of the hurricane. Miller [85] has investigated what this influence should be by computing the minimum pressure that could occur in a hurricane if it were a function of the temperature of the sea surface over which it travels and upper-air temperatures. His computational method, which is basically derived from parcel thermodynamics, is as follows: Surface air in the rain area around the hurricane center with temperature equal to the underlying sea surface is lifted to the highest level to which rising air would ascend assuming parcel ascent (i.e., to the level at which the lifted parcel temperature is no longer higher than the environment temperature). Then it is assumed that this air descends in the eye of the hurricane. This descent is not dry adiabatic, but it is assumed that the air mixes with saturated air at the edge of the eye so that it warms at a rate somewhere between the dry and moist adiabatic rates. The resultant mean temperatures are used to estimate thickness for the layer from the top level of parcel ascent to 800 mb. Assuming standard atmosphere height of the upper pressure level one can obtain an 800-mb height, which in turn can be converted to sea-level pressure by assuming a mean temperature for the lower layers. Miller's graph for minimum central pressure as a function of sea-surface temperatures for the case when the upper level of parcel ascent is 100 mb is shown in figure 28.

Miller made computations for eight hurricanes of 1954 and 1955 which are compared with observed minimum pressures in table 4. In five of the eight storms the computed pressure was within 5 mb of

Table 4 - Calculated minimum pressure (P_C) versus observed minimum pressure (P_O) for eight hurricanes (table 2 of [85]).

Hurricane	P_C (mb)	P_O (mb)
Carol, 1954	935	960
Edna, 1954	935	940
Hazel, 1954	937	937
Connie, 1955	938	936
Diane, 1955	949	969
Hilda, 1955	930	951
Ione, 1955	939	938
Janet, 1955	915	914

the observed pressure. Of the three which differed most from the computed values Diane moved over colder water before the full computed deepening could be realized and Hilda was twice disrupted by passage over land masses. In every case there was an appreciable time lag, generally 24-48 hr, between the time at which the minimum pressure was computed (computations were made once a day while these storms were south of 35°N) and the observed minimum pressure. This suggests that the time required for completion of the cycle of inflow at the surface, lifting to the upper troposphere, and descent of some of this air in the eye is of the order of 24-48 hr.

It must be re-emphasized that computations such as these can only approximate the potential maximum intensity of a storm, given the water temperatures over which the storm is moving and the associated upper-level temperatures. As mentioned earlier, formation and intensification of hurricanes and tropical storms are at least equally dependent on dynamical processes both in the lower and upper troposphere.

Rate of Development

The length of time required for an initial closed cyclonic circulation to develop into a storm of full hurricane intensity varies within wide limits. For example, Willett [160] gives a range of from 1 or 2 to 5 or 6 days. This variation is obviously dependent upon the net effects of the various physical factors influencing deepening of the tropical storm, but as yet all of these factors cannot be measured with sufficient accuracy to quantitatively predict precise rates of intensification. Even when fairly good evidence is at hand that one or more of these processes is acting in the direction of intensification, there is no assurance that other factors not so well known will not act to cancel these effects. For example, Riehl [124] describes a case where unusually heavy rainfall, comparable to that found in mature typhoons, was observed in a wave south of Guam. This heavy rainfall, of course, was a good indication that large amounts of condensation energy were being made available. Yet the wave traveled with little development all the way into the China Sea; proof that condensation energy alone cannot produce an intense hurricane.

Generally the time required for a hurricane to form on the ITC is longer than that required for one to reach maturity along an easterly wave, averaging roughly 5 or 6 days against 2 or 3. Several factors appear to be responsible for this difference. First deepening takes place more rapidly at a high than at a low latitude, due to the greater value of the Coriolis acceleration at the northern latitude. Secondly deepening takes place more rapidly within a region of strong as against a weak pressure gradient, because of greater cyclonic wind shear in areas of stronger winds, which makes a greater contribution to the initial cyclonic vorticity. Dunn's investigation [26] of the geographical locations in which storms reached hurricane intensity showed that the region where the trade winds attain their maximum velocity was a favored location. In both these cases the easterly wave is more favorably located than the ITC zone. Thirdly, the initial disturbance forming in the ITC zone is less likely to come under the influence of high-level fields of divergence, since the latter are found more frequently over the region of the lower-level subtropical easterlies.

On occasion hurricanes develop very rapidly, even in a matter of hours instead of the usual period of several days. Unfortunately, this "explosive" effect is not usually predictable at the present time, and in view of the serious consequences when such rapid deepening takes place close to a coastal area, it should be made the subject of intensive research.

MOTION

CLIMATOLOGY

Tracks

Collections of tracks of tropical cyclones for any given period or area show a wide variety of curves (cf., [88] or [151]). It is possible, however, to select a few basic tracks which broadly typify many of the individual tracks actually encountered. The tracks may be divided into three main groups: 1. those moving in the easterlies all the time, 2. those recurving from the easterlies to the westerlies, and 3. those moving in the westerlies all the time. Classification of tropical storms of the last 70 years according to these three broad categories shows that approximately 60 percent fitted category 2, 30 percent were in category 1, and 10 percent were in category 3 [155]. Similar categories of tropical cyclone tracks have been designated and illustrated by Willett [160] and schematically illustrated by Riehl [125]. Although typical shapes of storm tracks are of basic interest to the forecaster, of more practical interest are the prevailing tracks taken by tropical storms in specific geographical areas in various months.

Figures 29-34 illustrate the prevailing tracks

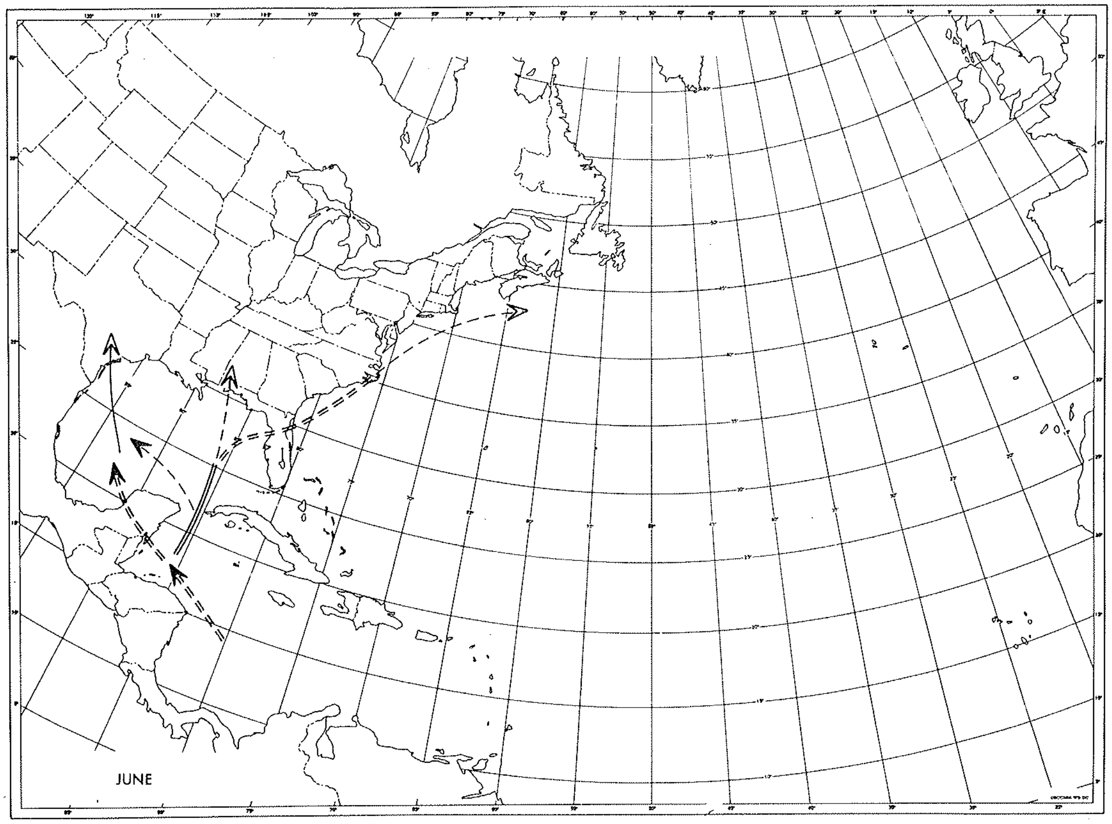


Figure 29. - Prevailing tracks of tropical storms in North Atlantic area in June. Solid lines represent primary tracks where a considerable number of storms have traveled, while dashed lines are secondary tracks where the number of storms involved is relatively few. The more well-defined tracks, which are indicated by double lines, are representative of travel of storms in the general direction and within about two degrees of latitude either side of the indicated paths. The less-well-defined tracks, shown by single lines, are only broadly representative of storm motion in their vicinity. The solid arrow on a track or a track origin is representative of a region of storm genesis, while an open arrow indicates either a rapid decrease in storm frequency or a wide scatter of tracks of storms in that region.

of tropical cyclones in the months June through November in the North Atlantic area. These tracks were derived by Ballenzweig from close inspection of the latest compilation of individual cyclone tracks made by the Office of Climatology [156]. In these figures solid lines represent primary tracks, where a considerable number of storms have traveled, while dashed lines are secondary tracks where the number of storms involved has been relatively few. The more well-defined tracks, which are shown as double lines, are representative of travel by tropical cyclones within about one degree of latitude either side of the indicated tracks. The less well-defined tracks, shown by single lines, are only broadly representative of the motion of storms in their vicinity. Naturally these tracks cannot represent the paths of all storms which occur in the particular month, for storms are found in many regions of the North Atlantic and in some places have no preferred direction. Thus, the absence of a prevailing storm track in a given area cannot be interpreted a priori as indicative of low storm frequency.

Frequencies of Direction of Motion and Median Speeds

Prevailing tracks of tropical cyclones are of

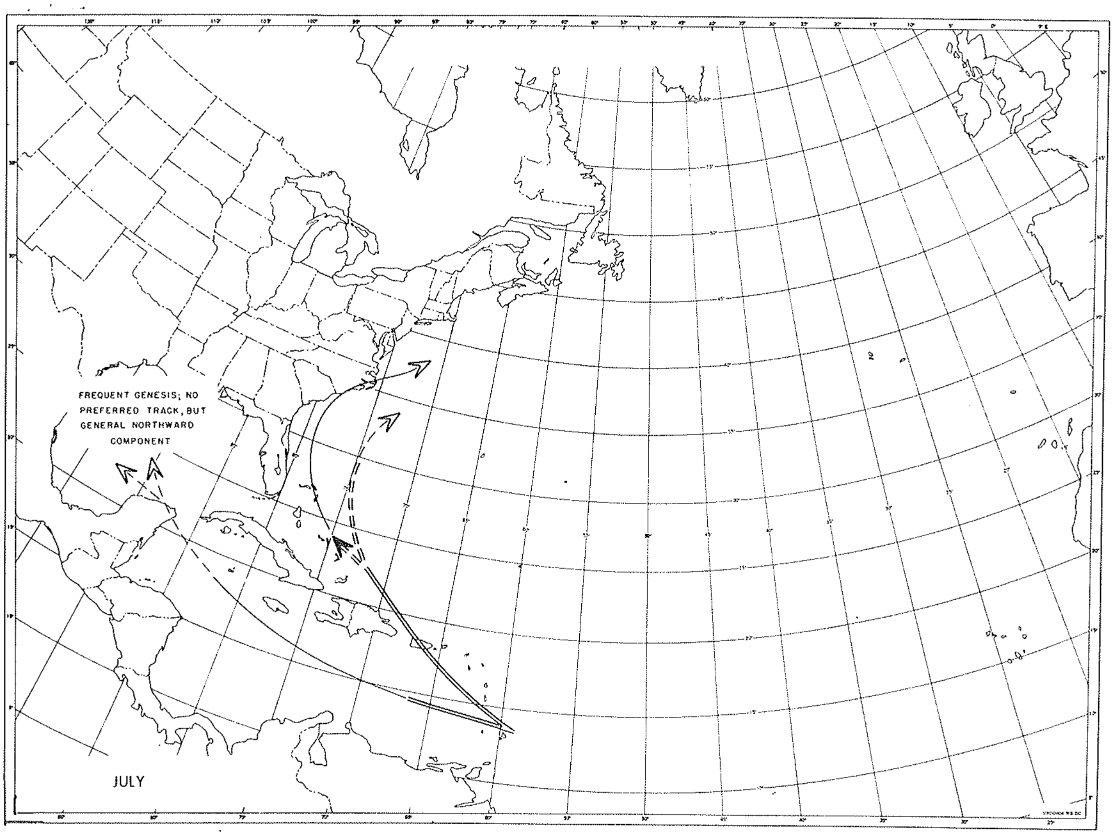


Figure 30. - Prevailing tracks of tropical storms in North Atlantic area in July. See legend to figure 29.

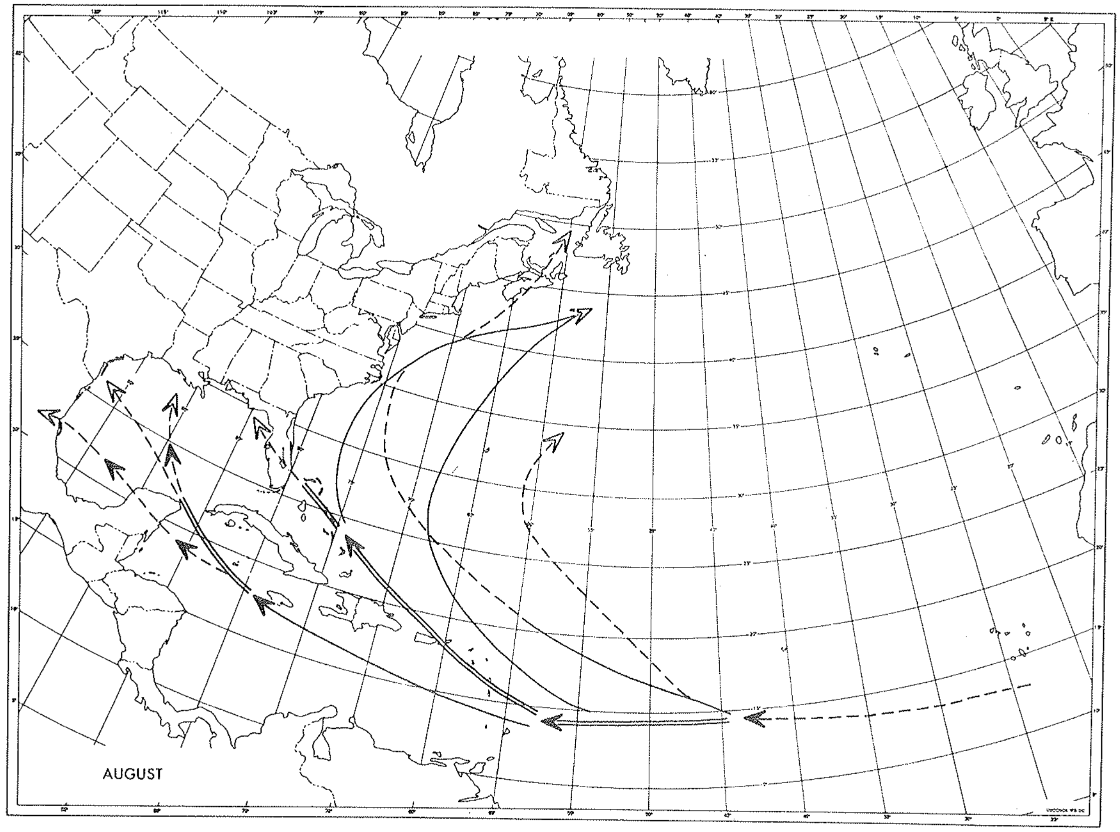


Figure 31. - Prevailing tracks of tropical storms in North Atlantic area in August. See legend to figure 29.

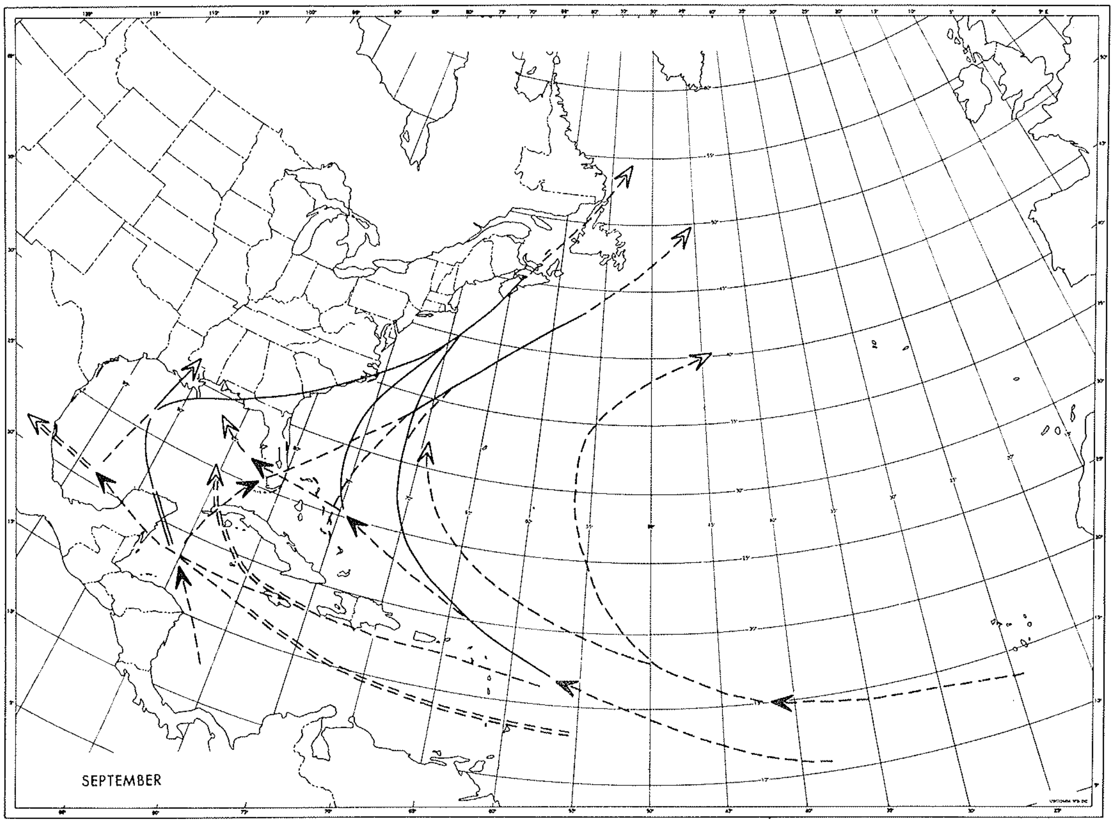


Figure 32. - Prevailing tracks of tropical storms in North Atlantic area in September. See legend to figure 29.

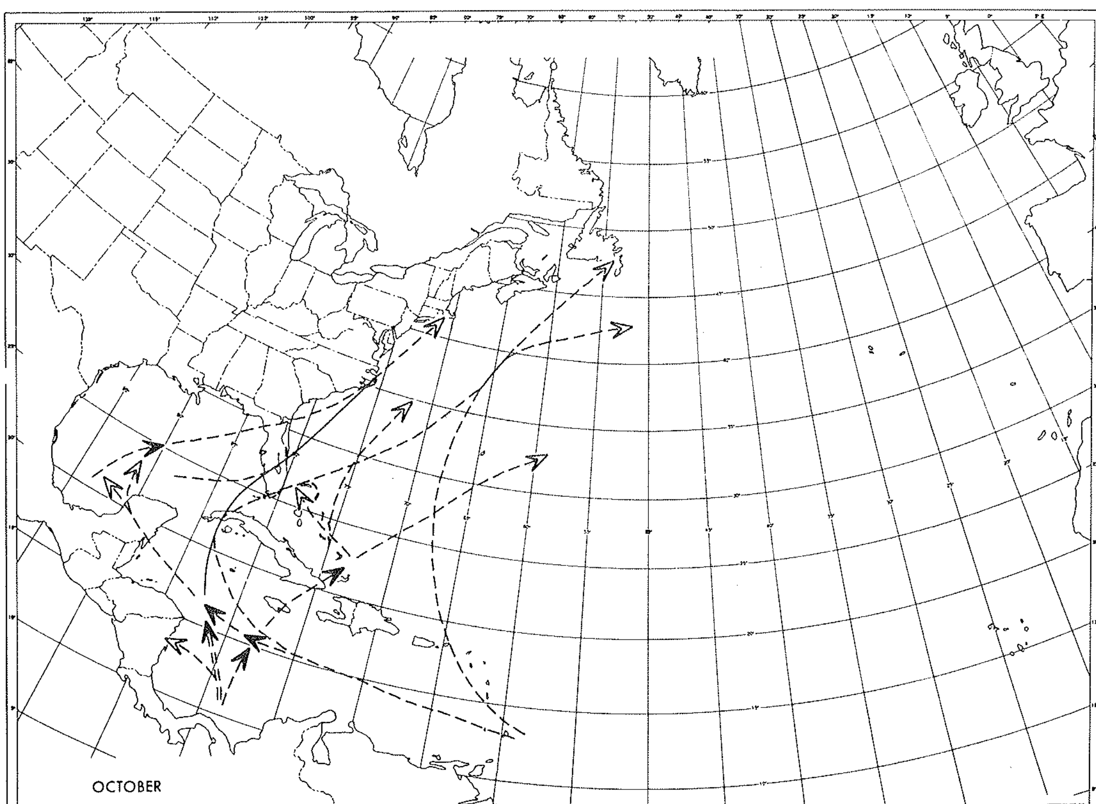


Figure 33. - Prevailing tracks of tropical storms in North Atlantic area in October. See legend to figure 29.

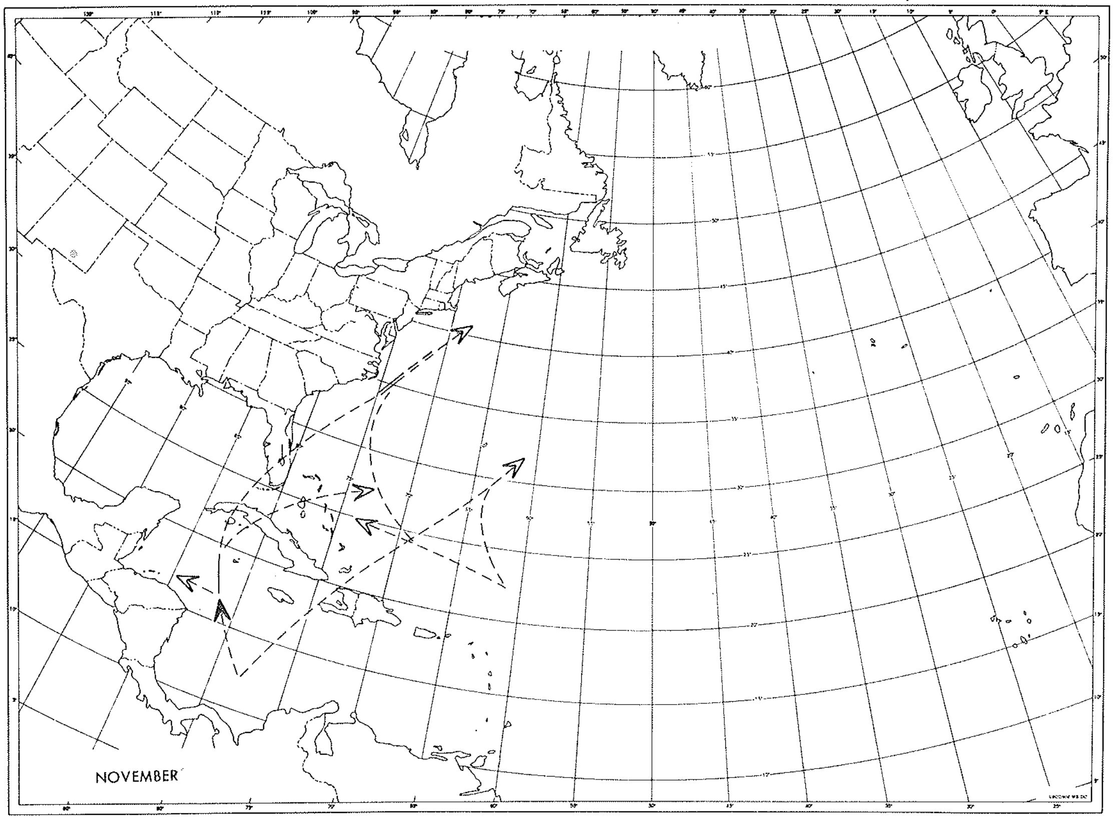


Figure 34. - Prevailing tracks of tropical storms in North Atlantic area in November. See legend to figure 29.

most use to the forecaster who is considering medium- and long-range prediction of tropical storms. For the more immediate periods of 12 to 36 hr more detailed climatological data on the direction and speed of a storm are useful. Figures 35-37, which were prepared by the Weather Bureau's Office of Climatology, provide information on the climatological behavior of tropical cyclones for the months August through October in each 5 deg lat-long area of the North Atlantic region. The lengths of the vectors in each box represent percentage frequencies with which storms in that area traveled in each of eight directions. The total number of storms whose motion could be determined in each box is given within the inner circle. Also the median speed of storms traveling in each direction is given in the appropriate corner or side of the box. (The median figure has been excluded whenever less than five storms traveled in the given direction.)

The use of these data by the forecaster is quite straightforward. However, a few examples may be instructive. First, suppose that a storm were located in the box centered at 22.5°N, 57.5°W in September (fig. 36). The overwhelming likelihood is that this storm would travel northwestward with a good estimate of the speed being 10 kt. Prediction of any other direction would require very strong evidence from forecasting tools. Secondly, take a storm located in September in the box centered at 27.5°N, 87.5°W. Here no direction of motion predominates except that a component of motion toward the north is most likely. The speed could be chosen once a direction is selected by other means or by averaging the median values. A third example would be a storm in the box centered at 27.5°N, 32.5°W. Here the previous history shows so few storms and such a scatter of directions that climatology is of virtually no value in giving a first estimate of the storm's motion.

It is anticipated that revised versions of figures 35-37 will be prepared and published by the Office of Climatology with maximum and minimum storm speeds for each direction also included. Similar charts will also be available for June, July and November. It will be noted that these charts represent a consolidation, revision, and expansion of data published a few years ago by Colón [15] who treated direction and speed separately.

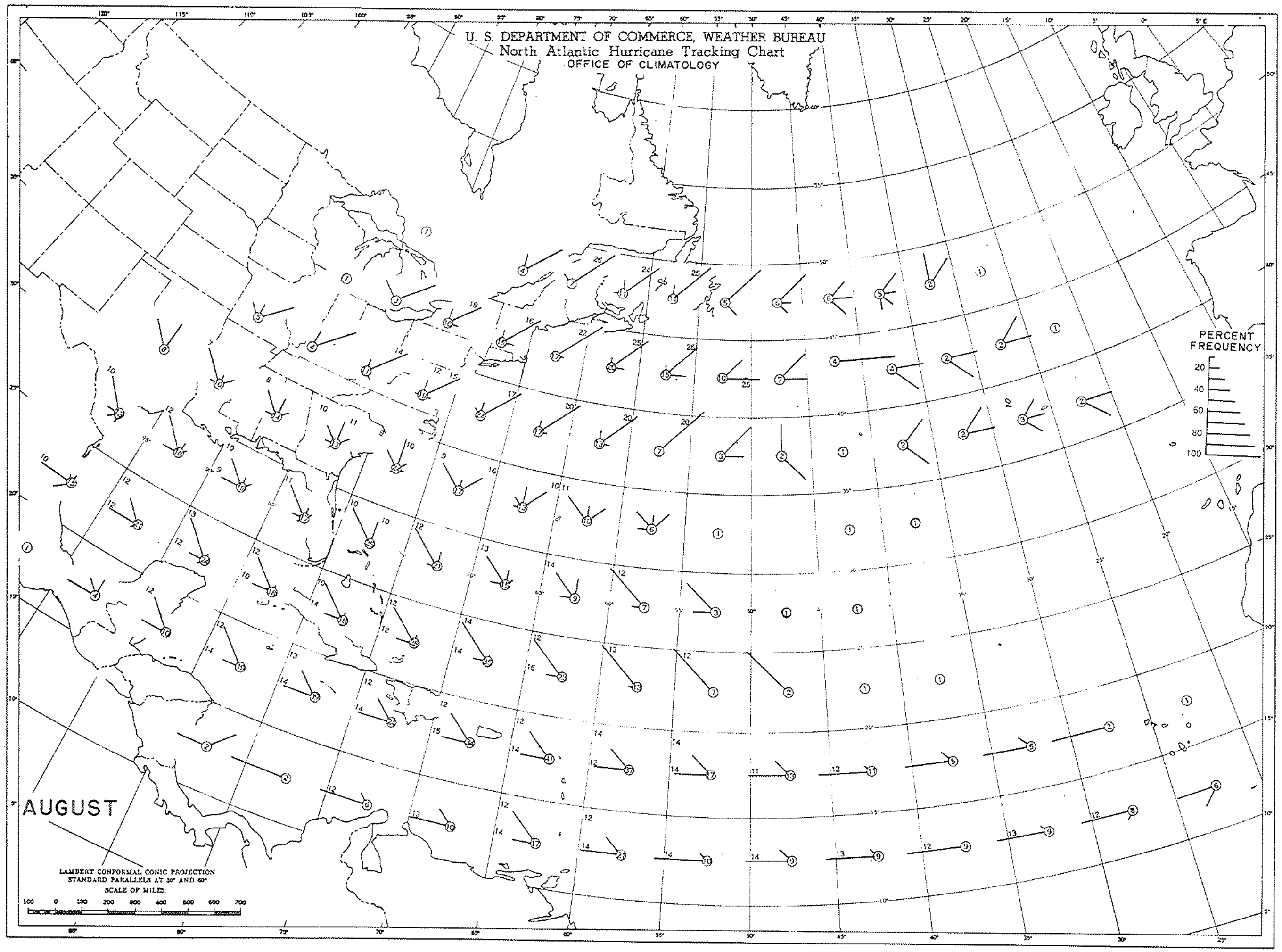


Figure 35. - Percentage frequencies of direction of motion and median speeds in each direction for tropical storms in each 5-deg lat-long box in the North Atlantic area in August. The lengths of the vectors in each box represent the percentage frequencies with which storms in that area traveled in each of the eight directions (see scale on right). The median speed (in kt) of storms traveling in each direction is given in the appropriate corner or side of the box (except whenever less than five storms traveled in the given direction). The total number of storms whose motion could be determined is given within the inner circle of each box.

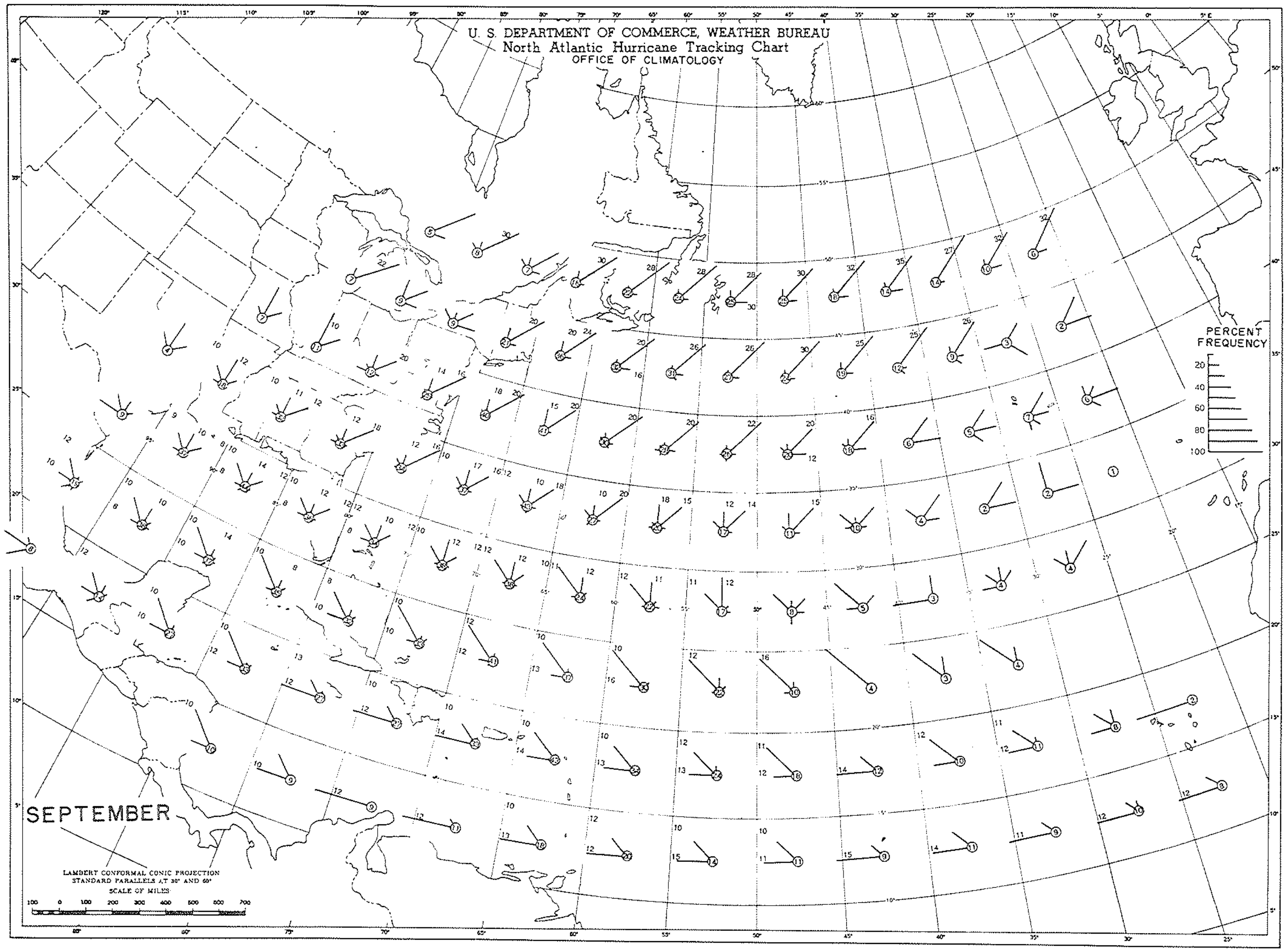


Figure 36. - Percentage frequencies of direction of motion and median speeds in each direction for tropical storms in each 5-deg lat-long box in the North Atlantic area in September. See legend to figure 35.

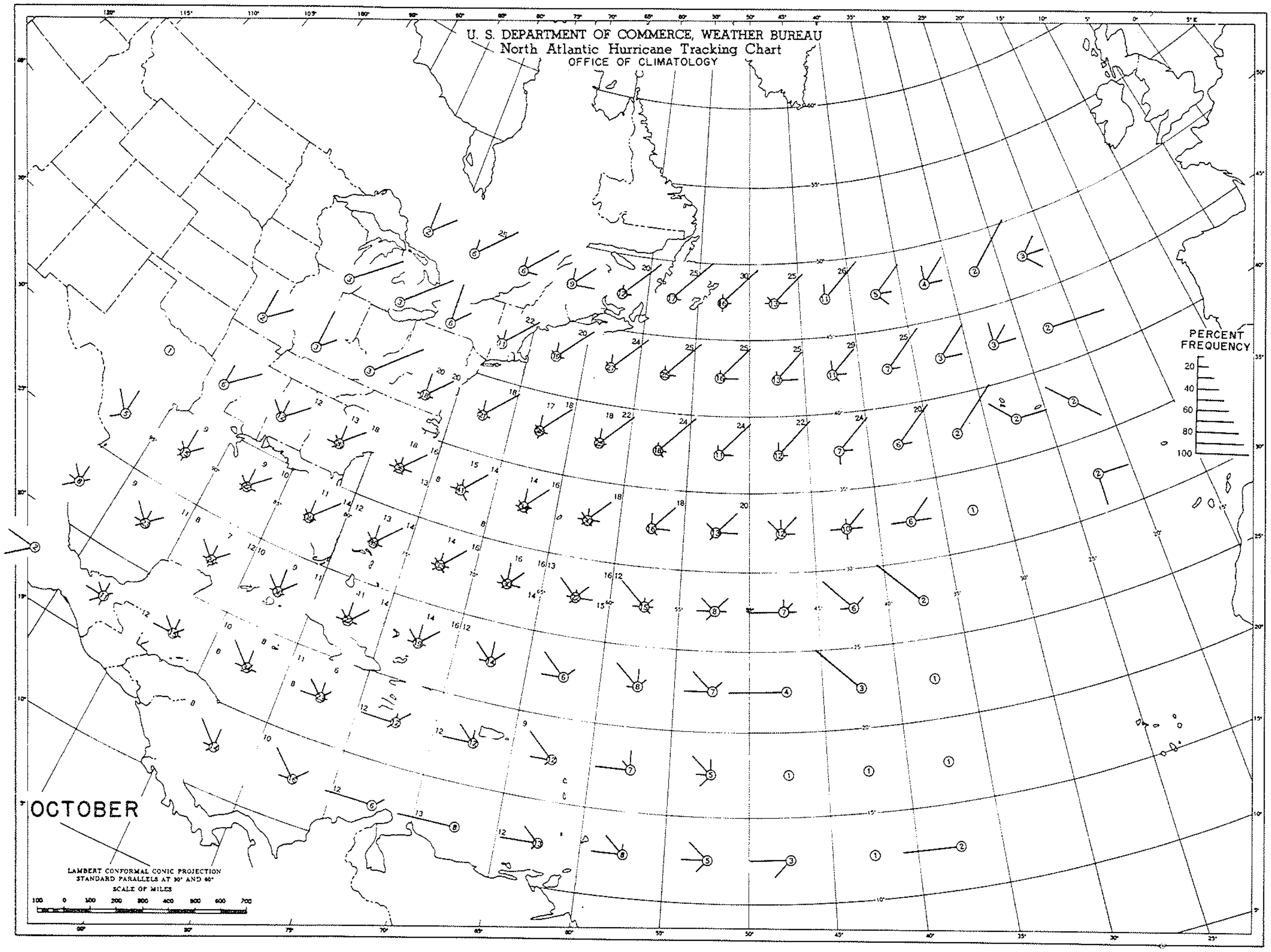


Figure 37. - Percentage frequencies of direction of motion and median speeds in each direction for tropical storms in each 5-deg lat-long box in the North Atlantic area in October. See legend to figure 35.

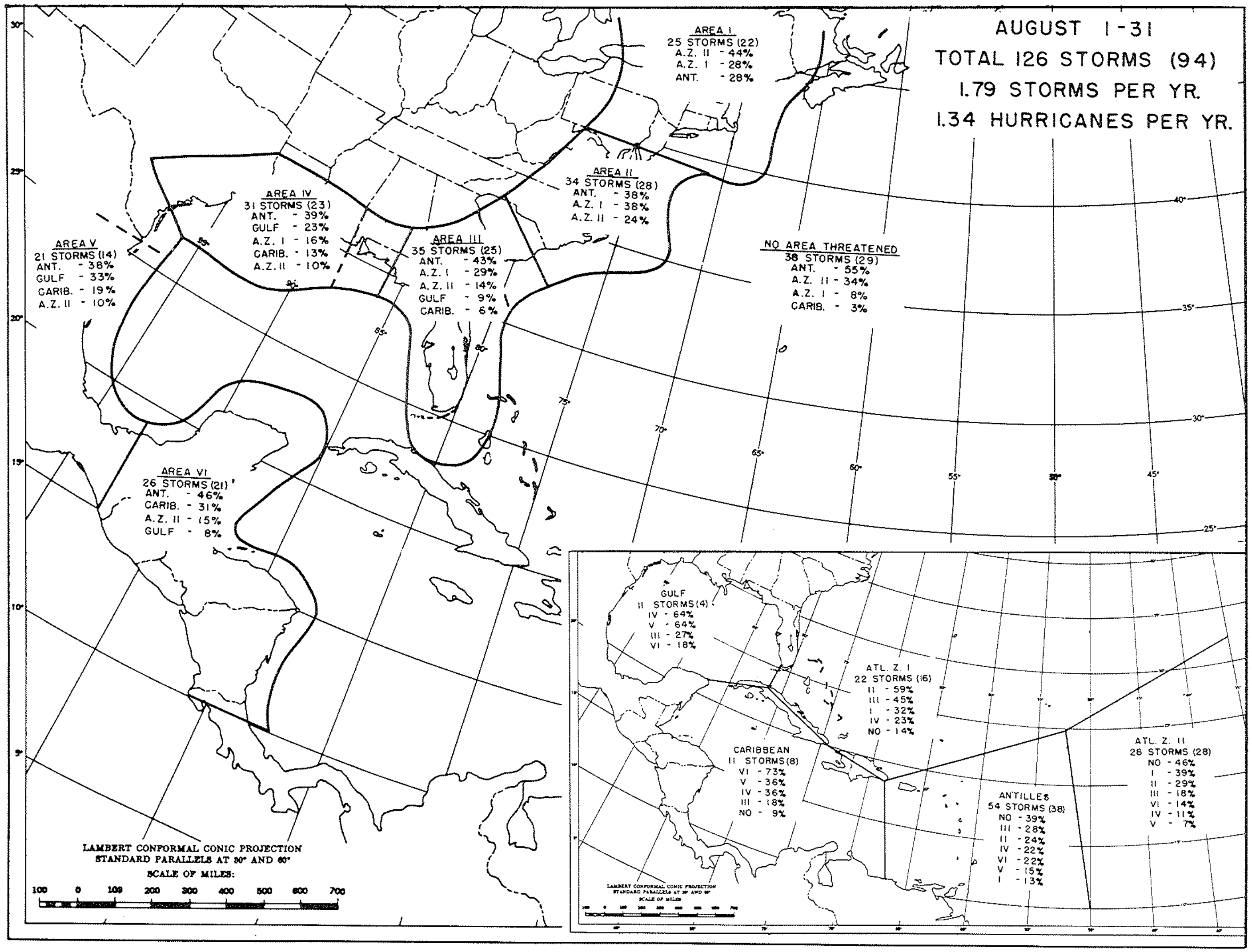


Figure 38. - Frequencies of tropical storms affecting coastal areas of the United States, Mexico, and Central America in August. Within each of the outlined coastal areas (and also the non-coastal area) are given the total number of storms affecting the area, the number of these storms which were full hurricanes somewhere along their tracks (in parenthesis), and the percentage of these storms originating in each of the designated regions of formation. Figures for each area of formation are given in the inset showing total number of storms which formed in each area, number of these which became hurricanes (in parenthesis), and the percentage of these storms which sooner or later affected the indicated coastal regions, or remained at sea ("no" area).

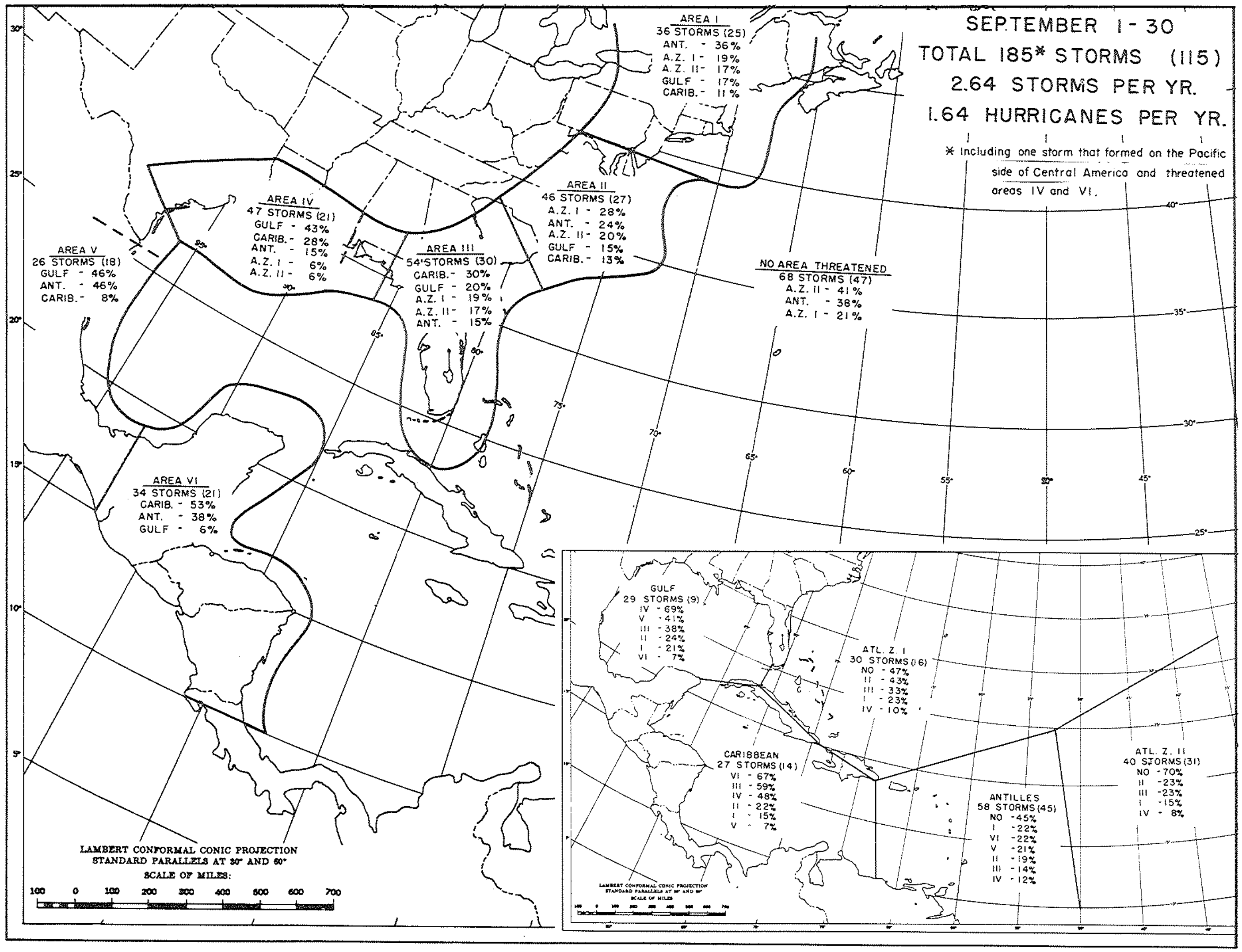


Figure 39. - Frequencies of tropical storms affecting coastal areas of the United States, Mexico, and Central America in September. See legend to figure 38.

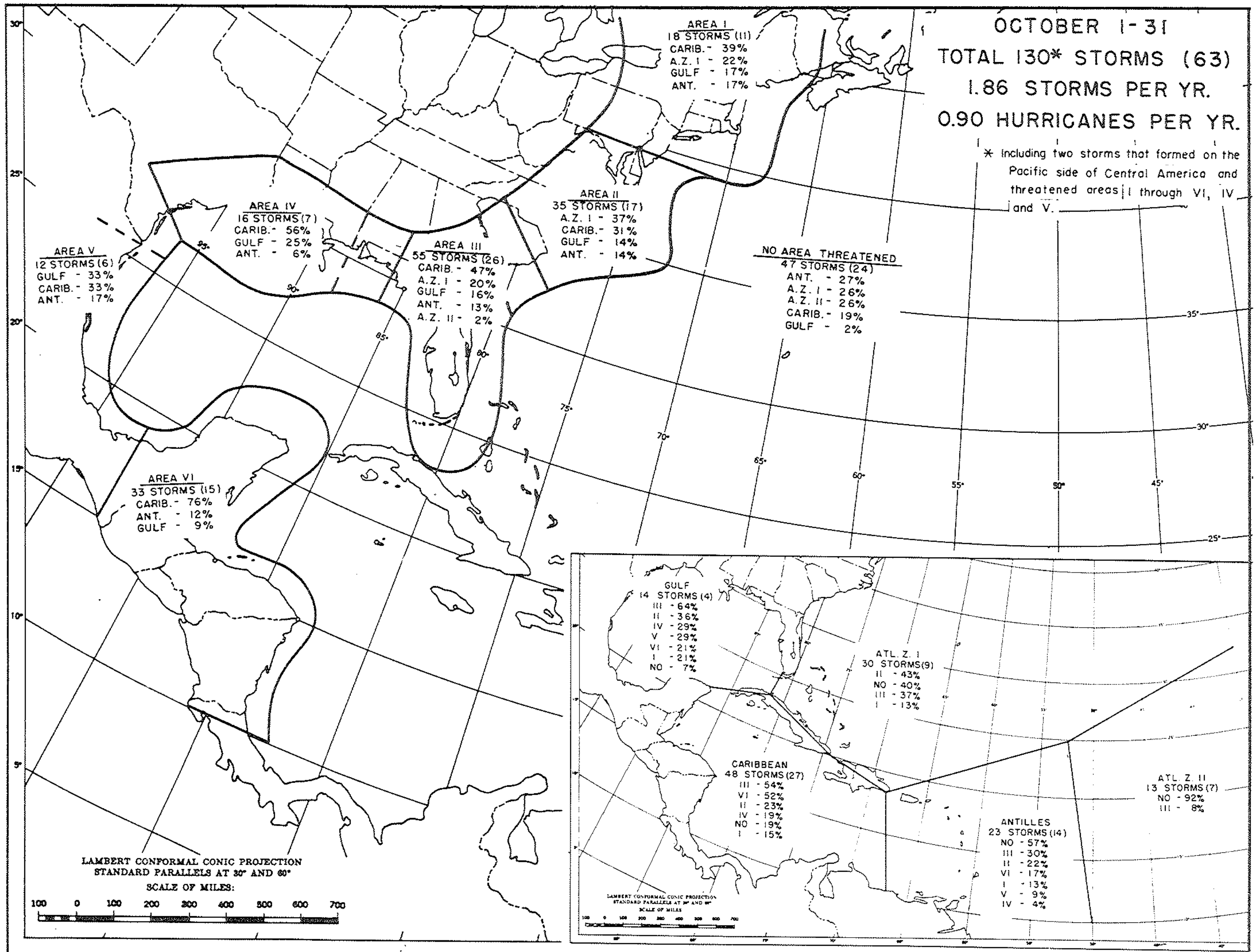


Figure 40. - Frequencies of tropical storms affecting coastal areas of the United States, Mexico, and Central America in October. See legend to figure 38.

Table 5 - Mean 3-day displacements of Atlantic hurricanes (1901-1955) according to latitude and current direction. (From table 2 of [128].) (Northward motion in deg lat, westward motion in deg long.)

Latitude (deg)		Current direction (deg) toward which storm is moving: 270 - 300	310 - 340	350 - 40
13 - 18	Northward	4	8	8
	Westward	12	4	-2
19 - 25	Northward	7	9	11
	Westward	8	3	-8
> 25	Northward	7	10	10
	Westward	4	-1	-11

In a way these figures provide the type of consolidation of information that was achieved by Mitchell's resultant vectors of motion [88], but it is believed that this treatment yields even more useful information in a single figure for each month.

Frequencies of Storms Affecting Coastal Areas of the United States, Mexico, and Central America

Since one of the forecaster's major tasks is to evaluate the chances of a storm affecting coastal areas, frequencies of storms influencing various portions of the coast are quite valuable. Ballenzweig has recently compiled such statistics for various coastal areas and subdivided them according to zones of formation. These are shown for the three most active hurricane months in figures 38-40. Note that these charts give two general types of climatological information. First, for each given coastal area (and also for the non-coastal area) figures are given for the total number of storms, the number of these which were full hurricanes somewhere along their tracks, and the percentage of storms originating in each of the designated regions of formation. Secondly, for each area of formation, figures are given (in the inset) for the total number of storms, the number of these which became hurricanes, and the percentage of these storms which sooner or later affected the indicated coastal regions, or remained at sea. These frequencies and others for June, July, and November will be published by Ballenzweig in the near future.

These charts cover all storms which entered the coast or came close enough to inflict some of the typical weather of tropical cyclones on coastal regions. Information of more limited scope, but also occasionally of special interest, is that covering storms which actually penetrated the coast. Figures showing where and at what angle hurricanes have entered the Gulf and Atlantic coasts of the United States may be found in [89] and [93]. Frequencies of tropical storms penetrating each segment of these coasts may be found in [155].

Three-Day Motion

Statistics of average displacements of storms for three days have been compiled by Riehl and Sanborn [128]. The data were subdivided according to initial latitudinal position of the storm and its initial direction of motion (i.e., taken from the track in latest 12 hr). The average meridional and zonal displacements for various latitude-direction categories are given in table 5 (negative values in the zonal category indicate eastward motion). As might be expected these figures portray the general tendency for storms in low latitudes to preserve their initial direction of motion while storms at higher latitudes generally tend toward recurvature to more of an eastward (or less westward) direction.

LONG- AND MEDIUM-RANGE PREDICTION OF MOTION

General Nature of the Problem

It is well recognized that the prevailing state of the large-scale circulation exerts some basic control on the paths of tropical (as well as extra-tropical) cyclones. In a rough sense, storms tend to be steered in the direction of the prevailing broad-scale flow in mid-troposphere. However, this concept is grossly over-simplified, for the relationships between storm motions and flow patterns are considerably more complex. Routine 5-day and 30-day forecasting experience in the past 15-20 years, numerous case studies, and a more recently inaugurated research project on this specific problem have yielded many more details about the role of the large-scale circulation in influencing motion of tropical cyclones.

Quite naturally the relationships are somewhat coarser the longer the period involved. Thus, when prevailing seasonal or monthly circulation patterns are considered, the most one can hope to determine are the general zones through which storms will travel and possibly whether they will move more rapidly or slowly than normal. On the other hand, for periods of about 5 days the problem becomes one of determining from the predicted 5-day mean flow and other information the tracks and speeds of individual storms.

Relationships for Monthly and Seasonal Periods

Over periods of a month or a season it is frequently found that tracks of tropical cyclones cluster about certain preferred axes. This appears to be especially true when the monthly circulation is dominated by some major planetary waves which are rather stable in position and intensity. Such persistence or recurrence of certain dominating features of the planetary circulation is frequently revealed very clearly by pronounced centers of height departure from normal. In fact, as illustrated by Namias [104], prevailing monthly tracks of tropical storms often parallel the isopleths of monthly height anomaly (i.e., "steered" by the anomalous flow). However, in many months when there are only one or two storms in the entire Atlantic, for example, the tracks are often not too clearly related to the monthly mean circulation, which essentially signifies that the broad-scale circulation state in existence during the life of the storm was not characteristic of the month as a whole.

Thus far the most satisfactory way of portraying relationships of tropical storm motion to monthly or seasonal flow patterns has been in terms of composite 700-mb height anomaly charts for seasons or months of frequent and infrequent cyclone occurrence in particular areas. First used by Namias [105] for the New England area in the fall season (September - November), this type of approach has since been extended to several other areas along the Atlantic, Gulf, and Caribbean coastlines of North and Central America by Ballenzweig [4], who worked with 700-mb mean charts derived especially for the "hurricane season" (August-October). Charts for two of six areas studied by Ballenzweig are shown in figures 41-44.

It is apparent that the years in which the north-

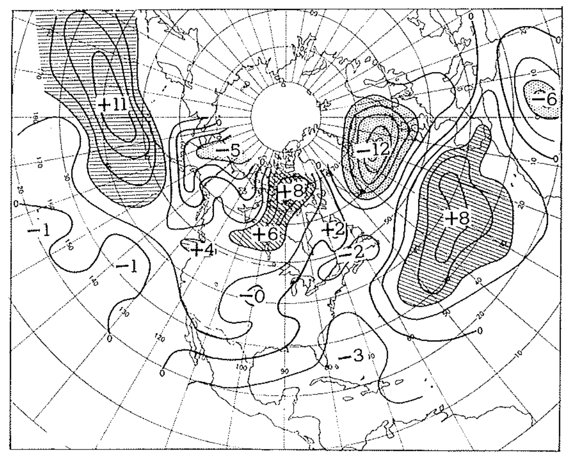


Figure 41. - Average departures from normal (in tens of feet) of 700-mb heights for the 6 seasons of maximum tropical cyclone incidence in the northeastern United States (Area I of fig. 38). (After Ballenzweig [4].)

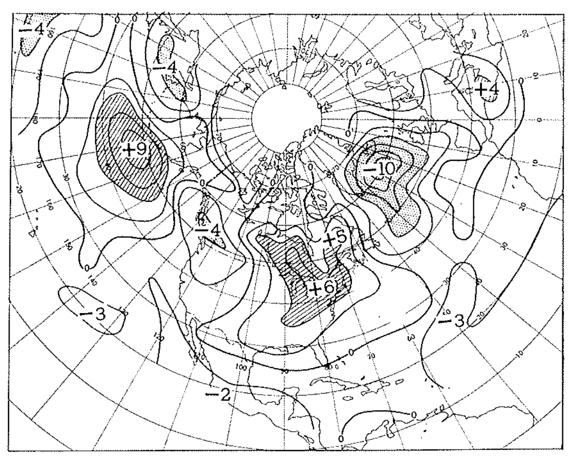


Figure 42. - Average departures from normal (in tens of feet) of 700-mb heights for the 5 seasons of minimum tropical cyclone incidence in the northeastern United States (Area I of fig. 38). (After Ballenzweig [4].)

eastern United States area was most vulnerable to hurricane activity (fig. 41) differ markedly in average anomaly pattern from the years in which the area was relatively invulnerable to hurricanes (fig. 42). The more northward and westward tracks which storms must take to attain a position where they would affect the Northeast are apparently related to northward displacement of the subtropical ridge in the Atlantic (as indicated by the large region of positive height anomalies at middle latitudes in the Atlantic in figure 41) and to southerly anomalous flow in the western Atlantic between the Atlantic ridge and a slightly deeper than normal trough near the east coast. On the other hand, in years when no tropical storms affect the Northeast, heights are above normal over the Northeast and generally below normal in the central Atlantic. This pattern is probably not favorable for frequent storm formation in the Atlantic in the first place (compare with the pattern accompanying frequent storm formation in the Atlantic in fig. 14) and secondly is favorable for storms moving northward farther out in the Atlantic or moving westward into the southern United States or the Gulf of Mexico.

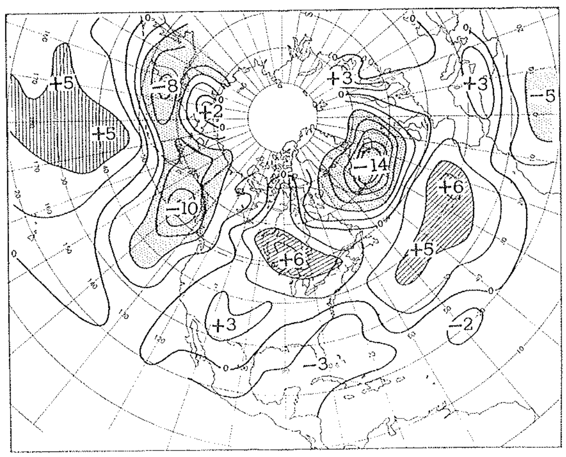


Figure 43. - Average departures from normal (in tens of feet) of 700-mb heights for the 6 seasons of maximum tropical cyclone incidence in the southeastern United States (Area III of fig. 38). (After Ballenzweig [4].)

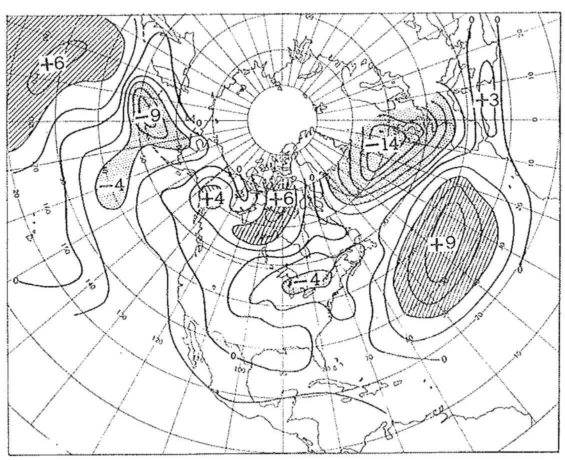


Figure 44. - Average departures from normal (in tens of feet) of 700-mb heights for the 6 seasons of minimum tropical cyclone incidence in the southeastern United States (Area III of fig. 38). (After Ballenzweig [4].)

For the southeastern United States (fig. 43) hurricanes are frequent when height anomalies are positive in the vicinity of the Great Lakes and in middle latitudes of the Atlantic while negative anomalies occur at lower latitudes. Thus, a broad band of anomalous easterly flow prevails at lower latitudes which tends to steer storms into a position affecting this area. By way of contrast the chart for those seasons with minimum tropical cyclone frequency in the Southeast (fig. 44) shows negative anomalies over the Great Lakes so that winds are offshore relative to normal along the coast from the Middle Atlantic States into the Southeast. This type of flow combined with strong southerly flow well out in the western Atlantic would definitely tend to keep tropical storms steered away from the Southeast.

These composite charts as well as the remaining charts for other coastal areas [4] serve as convenient guides for the likelihood of tropical storm tracks in the areas concerned, when the predicted circulation anomalies bear some resemblance to any of these composite patterns. Although developed for seasonal data these charts have been found to be equally applicable for circulation patterns and tropical cyclone frequencies for monthly periods. Indeed it is in the monthly forecast procedure that these relationships are being put to practical use. It is also believed that many of these relationships are adaptable to shorter periods as will be seen from some of the reasoning used in 5-day forecasting of hurricane motion as described below.

Relationships for 5-Day Periods

To predict the motion of hurricanes for periods of about two to seven days (i.e., medium-range prediction) it is necessary to forecast the state of the large-scale circulation and its evolution over periods of several days with some precision.* In

*A recent preliminary study by Cook [17] has attempted to relate hurricane motion for three days to the current space-mean chart for the layer 1000-200 mb and the latest observed 48- and 72-hr changes in this flow pattern. This method may prove useful for the period mentioned, but it is doubtful that one could proceed as far out as 4 to 7 days without use of prognostic flow patterns.

periods of rapid change this is especially difficult, and to a great extent the failures in accurate prediction of hurricane tracks are attributable to errors in prognosticating the mean flow patterns. However, it is hoped that better skill in predicting the detailed evolutions of mean flow patterns will be attained in the near future with the application of more precise numerical methods to 5-day forecasting [106]. If the hurricane is not already in existence at the time the prediction is made, the forecaster has a most difficult task since he must first determine if, when, and where a storm will form. For this he must consider the many factors favorable for storm formation which were discussed earlier. Even if the storm is already in existence, a forecast of the track and moreover the daily position of the storm for several days in the future is often extremely dependent on its behavior in the first few days. This is particularly true in those borderline cases when the circulation pattern is either indefinite or changing quickly so that the storm's chances of moving out of the Tropics may be dependent upon its arrival at the proper location at just the right time to be picked up by a passing westerly trough. Although at times the precise track which a storm takes seems to be dependent upon a whole series of fortuitous coincidences which defy longer-range prediction, the motions of a majority of storms appear to be fairly well prescribed by the large-scale circulation. Some of the more characteristic relationships between hurricanes and the concurrent large-scale circulation patterns (generally using 5-day mean flow at 700 mb) are given below:

Motion in the Subtropical Easterlies - Tropical storms predicted to be located under a broad subtropical easterly current usually travel in the direction of the 5-day mean contours at 700 mb. Also, storms are steered rather well by the mean flow on the south and southwest sides of a strong subtropical anticyclone and around the northeast, north, and even northwest sides of a well-developed mean tropical low. These relationships hold best when the mean flow patterns are well-defined and when the cyclone is of relatively small dimensions. In cases when the flow is expected to be poorly defined the motion of the storm may be erratic and some smaller-scale forces may dominate its motion. However, it should be pointed out that even when the flow in the immediate vicinity of the storm appears chaotic, the broader-scale mean flow over a distance of several hundred miles surrounding the storm may be relatively well-defined and the storm may at least have a significant component of motion in the direction of this flow.

When a hurricane becomes a large cyclonic vortex (this happens more frequently in the western Pacific), it essentially becomes a mean tropical cyclone which must be dealt with in the same manner as other features of the mean flow pattern [102]. Frequently there are good indications for the future motion of such a large-scale system.

Recurvature - The dominant role of the planetary waves in influencing recurvature, even in shorter-period forecasting, has been stressed by Riehl [125]. For medium-range prediction of hurricane recurvature the problem of wave behavior for several days in the future comes to the fore. And, of course, it has been demonstrated frequently that events in distant portions of the hemisphere can play a crucial role in long-wave developments in the area of interest.

Let us first consider the types of long-wave situations which are favorable and unfavorable to recurvature and then discuss cases when rapid changes occur in the large-scale flow.

1. Flow patterns associated with recurvature.

a. Large-amplitude mean trough, extending southward from the westerlies and located within a few hundred miles to the west of the center. - If the trough is stationary or slow moving, the storm will remain well to the east of the upper trough as it moves northward. In this case it will be "steered" by the southerly flow components ahead of the mean trough. If the mean trough is moving eastward at a moderate pace or if the storm forms at the southern end of the trough, the track of the storm may be directly along the mean trough line or even slightly to its rear by the time it reaches middle latitudes. Some typical examples

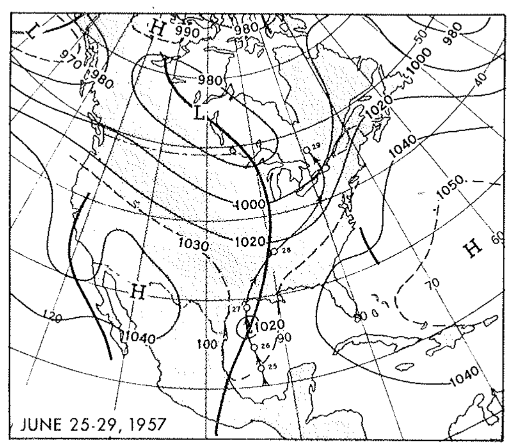
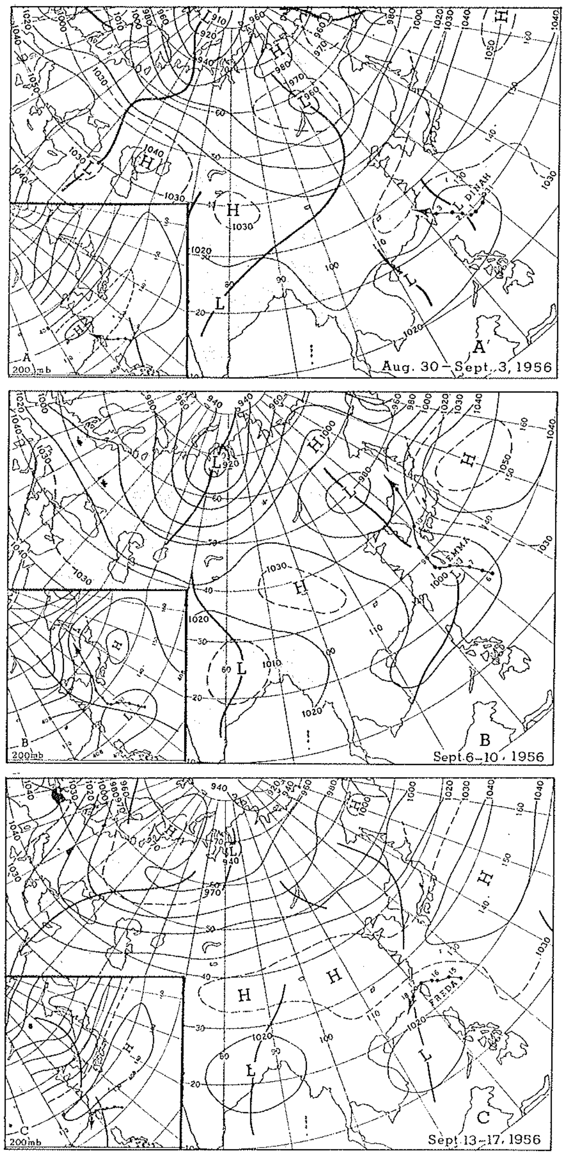


Figure 45. - Track of hurricane Audrey at sea level in relation to 5-day mean 700-mb circulation pattern, June 25-29, 1957. Open circle and date along storm path shows position at 1200 GMT. (After Klein [76].)



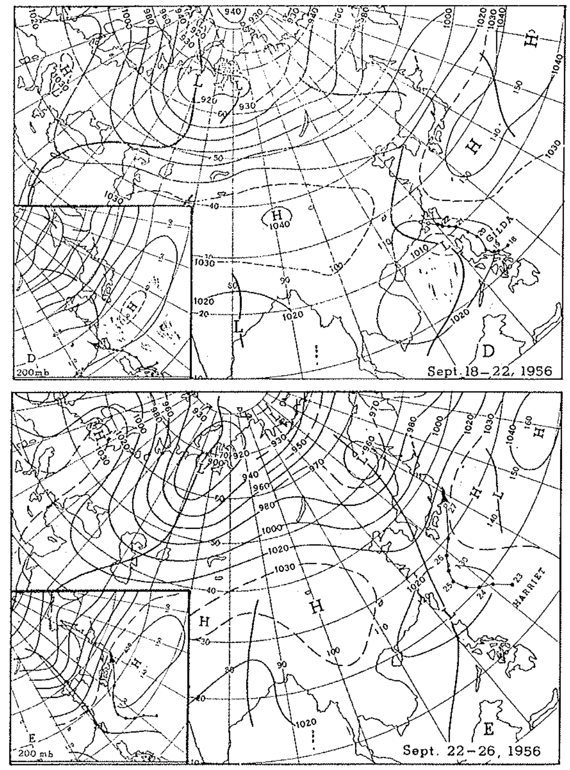


Figure 46. - Typhoon tracks at sea level in relation to 5-day mean circulation patterns at 700 mb and 200 mb (inset), September 1956. Circles along tracks show 12-hr locations with dates at 0000 GMT positions. (After Hawkins [45].)

of recurving tropical storms in relation to concurrent 5-day mean 700-mb and 200-mb flow patterns are shown in figures 45, 46B, and 46E, which are from articles by Klein [76] and Hawkins [45]. In discussing the two typhoon cases Hawkins has pointed out that pronounced wave amplitudes existed farther upstream as well as in the immediate trough to the west. Such upstream amplitudes would tend to insure preservation of the amplitude of the trough which is directly influencing the storm's recurvature, provided that the wave features upstream are at a relatively stable wave-spacing from the trough in question.

b. Well-marked low-latitude trough building northward into the westerlies. - Occasionally when the hurricane is associated with a large-scale mean trough or cyclone in the subtropics the storm will recurve in the general vicinity of this trough as the latter opens up toward the westerlies. Sometimes this type of trough will actually shift the recurvature of the storm to higher latitudes, especially if the storm is moving northwestward in the northeast quadrant of a mean low. Also this type includes large hurricanes which themselves have the dimensions of planetary wave systems. An interesting example of tracks associated with this type of mean pattern is shown in figure 47, which is from an article by Hawkins [44]. In this case a pair of hurricanes recurved in the western Atlantic where a broad subtropical mean trough was located.

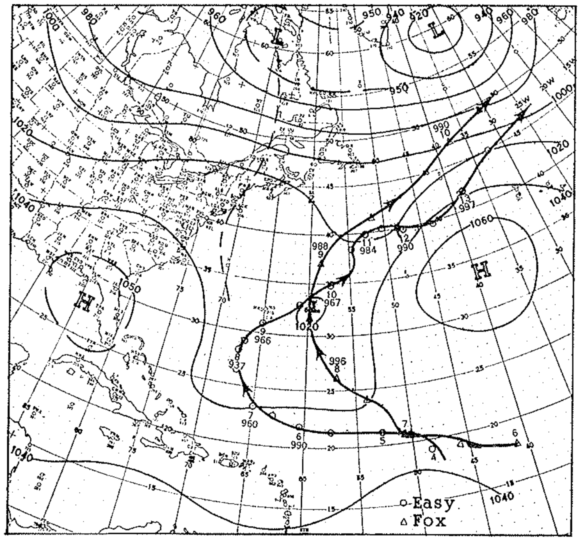


Figure 47. - Tracks of hurricanes Easy and Fox at sea level superimposed on 5-day mean 700-mb circulation pattern for September 8-12, 1951. Circles (for Easy) and triangles (for Fox) indicate 12-hr locations with dates and approximate central pressures (in mb) at 1230 GMT positions. (After Hawkins [44].)

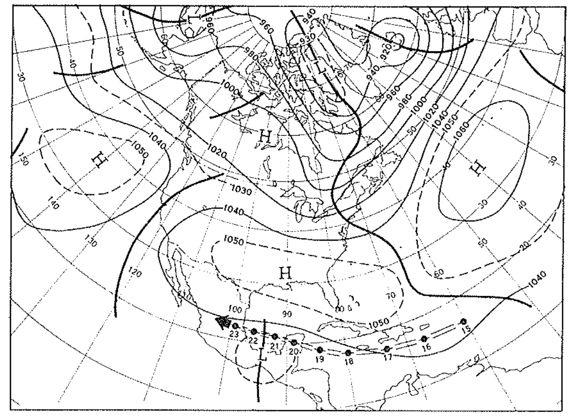


Figure 48. - Track of hurricane Charlie at sea level superimposed on 5-day mean 700-mb circulation pattern for August 18-22, 1951. Dots and dates are for 1230 GMT positions of storm.

c. Weak trough between two separate subtropical high cells. - In some cases tropical storms move northward through very weak breaks in the subtropical highs. These are usually difficult to predict since the development of such breaks involves relatively minor height falls in mid-troposphere. Elongated subtropical highs will often break into smaller cells as the westerlies to the north decrease in intensity and vorticity effects tend to favor shorter wave spacings.

2. Flow patterns associated with non-recurvature.

a. Strong subtropical anticyclone or ridge to the north of the storm with mean trough in westerlies located rather far west of the longitude of the storm. - In essence this is the circulation pattern which steers the storm westward in the tropical oceans. If this pattern develops strongly over the western oceans or continents a storm will generally be driven inland and dissipate before it gets a chance to recurve on the extreme western edge of the ridge. An accompanying characteristic of this type of pattern is that the westerlies are far to the north, particularly at the longitude of the storm. Figures 46A and 48 illustrate two typical cases of non-recurving storms associated with this basic flow pattern.

b. Westerlies flat (i.e., small-amplitude waves) and at latitudes near or north of normal. - A narrow subtropical ridge separates the westerlies from the tropical trough. In many cases a mean trough in the westerlies may be located near the same longitude as the storm. Cases with this latter characteristic are extremely difficult to handle since the differences from the third type (c) of recurving cases above can be rather subtle. Figures 46C and 46D illustrate this type of situation. In these critical cases, as well as in the other cases of figure 46, Hawkins [45] has demonstrated that the 200-mb mean flow may provide some additional indications as to whether recurvature will occur.

3. Importance of rapid changes in planetary waves.

Fundamental changes in planetary waves occasionally occur at the time when a hurricane approaches the region of possible recurvature. In several cases flow patterns alter so much that the storm takes a radically different track than might have been expected from the original state of the large-scale circulation. A spectacular example of such a situation was the case of the severe Atlantic hurricane of September 1947 which originally appeared to be recurving off the east coast of the United States, but instead moved westward across Florida and the Gulf of Mexico into Louisiana, as a huge anticyclone developed over the northeastern United States. Klein and Winston [77] demonstrated how this anticyclone developed as a result of long-wave amplification which originated in a newly-developed, deep trough in mid-Pacific and propagated downstream to the eastern United States within two to three days.

Long-wave amplification played a different, but equally important role in the tracks of three major hurricanes (Carol, Edna, and Hazel), which

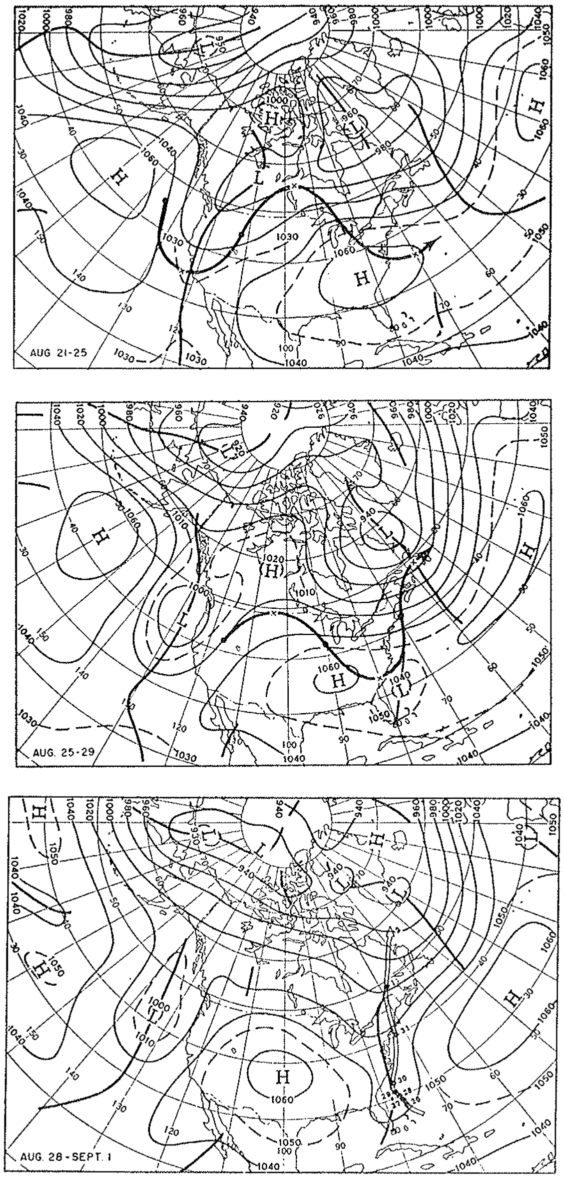


Figure 49. - Sequence of 5-day mean 700-mb charts showing trough development along east coast of United States and path of hurricane Carol northward along mean trough line during period August 28-September 1, 1954. Constant absolute vorticity trajectories show how upstream circulation developments in eastern Pacific and western North America led to retrogression of anticyclone over Southeast and trough development over eastern United States. (After Winston [161].)

moved northward along the east coast of the United States in 1954. In all three cases long-wave troughs deepened between the Mississippi Valley and the east coast just when the storms were near the recurvature stage off the southeastern coast. These timely trough intensifications effectively insured rapid accelerations of these three hurricanes northward along the east coast. It has been pointed out in each case [62, 79, 161, 162] that the deepening of the trough over eastern North America appeared to be due to energy dispersion from prior wave amplification at least as far upstream as the Pacific area. Figure 49, from a paper by Winston [161], illustrates the strong indications emanating from the Pacific and western North America for mean trough development along the east coast at times prior to and after Carol's formation in the Bahamas on August 25, 1954. Note that the initial flow pattern in the eastern United States, if it persisted with little change, would be strongly against the motion of a hurricane northward along the east coast.

In the case of Hazel (fig. 50) the large-scale flow pattern which existed over eastern North America and the western Atlantic at the time Hazel was still over the West Indies (Oct. 12-13) would have suggested that the storm might be steered into the southeastern coast in the vicinity of Florida or Georgia and then would probably dissipate over land. However, as Krueger [79] and Hughes et al [62] have pointed out, cyclogenesis took place in the east central Pacific between October 13 and 14 which started a rapid amplification of the ridge along the west coast. The trough in the central United States moved quickly eastward to the Mississippi Valley as a result of the short, upstream wavelength and deepened rapidly in response to the energy dispersion from upstream. Needless to say the southerly flow over the east coast, between this intensifying trough and the stationary anticyclone in the western Atlantic, increased rapidly and Hazel was carried northward at a quickly accelerating pace.

Motion in Temperate Latitudes - Once a hurricane has moved into temperate latitudes it is usually steered rather well by the broad-scale flow patterns in much the same manner as an extratropical cyclone. It will move eastward or northeastward if it encounters a well-marked westerly or southwesterly current in middle latitudes. If the trough with which it is associated has strong southerly or southeasterly flow extending northward toward higher latitudes the storm may proceed far northward or northwestward as in the cases of Carol (fig. 49) and Hazel (fig. 50). When the circulation at middle latitudes is broken down into vortices with a blocking anticyclone to the north of the storm, the hurricane is likely to move in an erratic, looping path and in some cases may even be steered back toward lower latitudes by northerly flow components associated with the blocking ridge aloft.

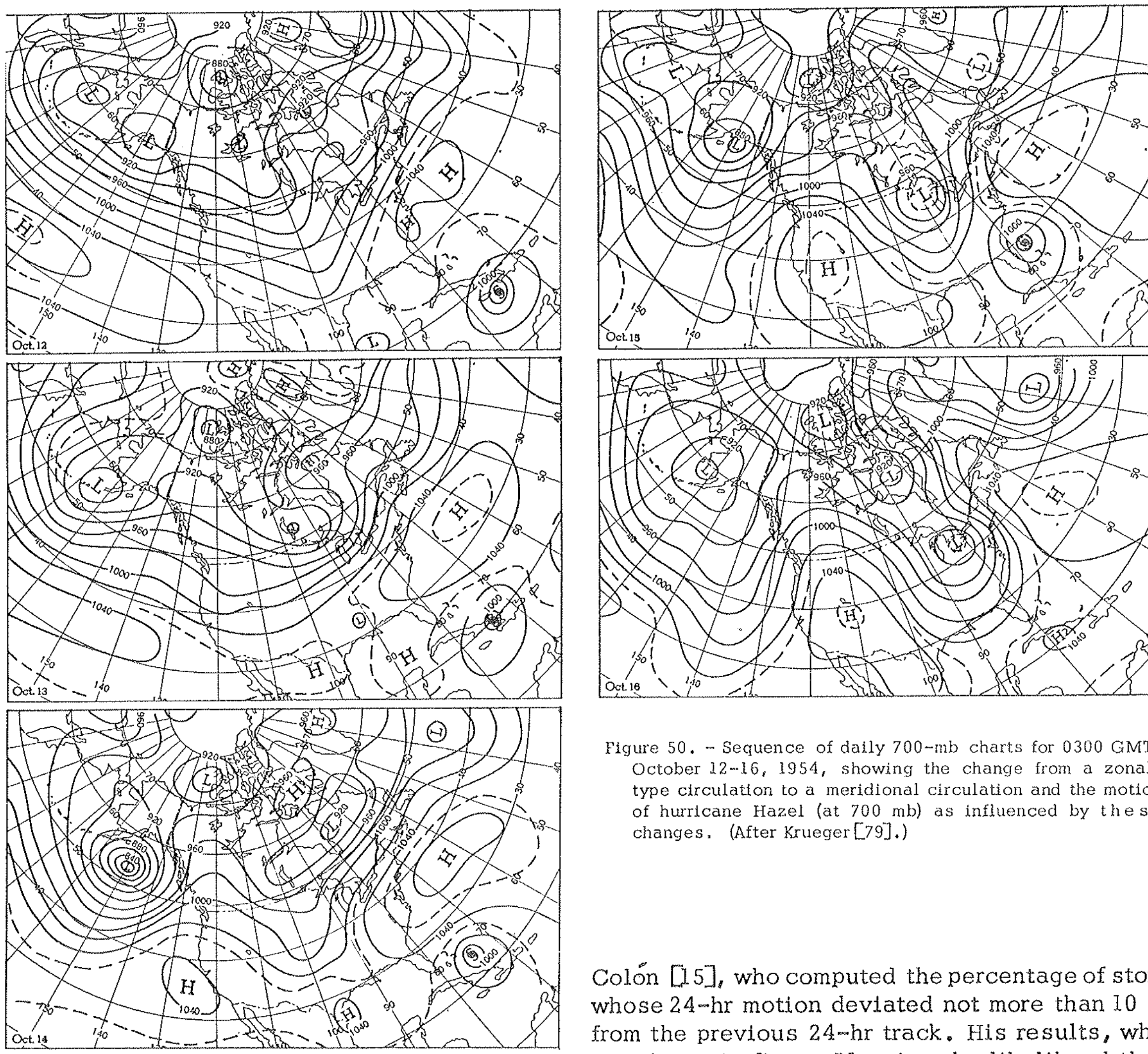


Figure 50. - Sequence of daily 700-mb charts for 0300 GMT, October 12-16, 1954, showing the change from a zonal-type circulation to a meridional circulation and the motion of hurricane Hazel (at 700 mb) as influenced by these changes. (After Krueger [79].)

SHORT-RANGE PREDICTION OF MOTION

Empirical and Simplified Physical Considerations

Continuity - After a storm has been tracked for some time with reliable fixes, it is very easy to extrapolate its past motion into the future. In fact, a continuity forecast generally serves as the first approximation to the storm's projected path for periods up to about 24 hr. The usefulness of simple persistence in forecasting the direction of motion of tropical storms was investigated by Colón [15], who computed the percentage of storms whose 24-hr motion deviated not more than 10 deg from the previous 24-hr track. His results, which are shown in figure 51, give the likelihood that a storm in a given location in a given month will move in a persistent fashion. The probability of success of a forecast based on persistence is relatively high on the average in the Caribbean Sea and in the eastern Atlantic in more southerly latitudes (except in November). Note that in relatively large areas the probability of persistence is more than 80 percent, which is a very good confidence factor for a forecasting tool. On the other hand, in the Gulf of Mexico and in more northerly areas (up to 35°N), the probability of success of a persistence forecast is generally small.

Colón's results apply only to straight-line persistence of direction. No figures are available for the degree of persistence in speed of motion.

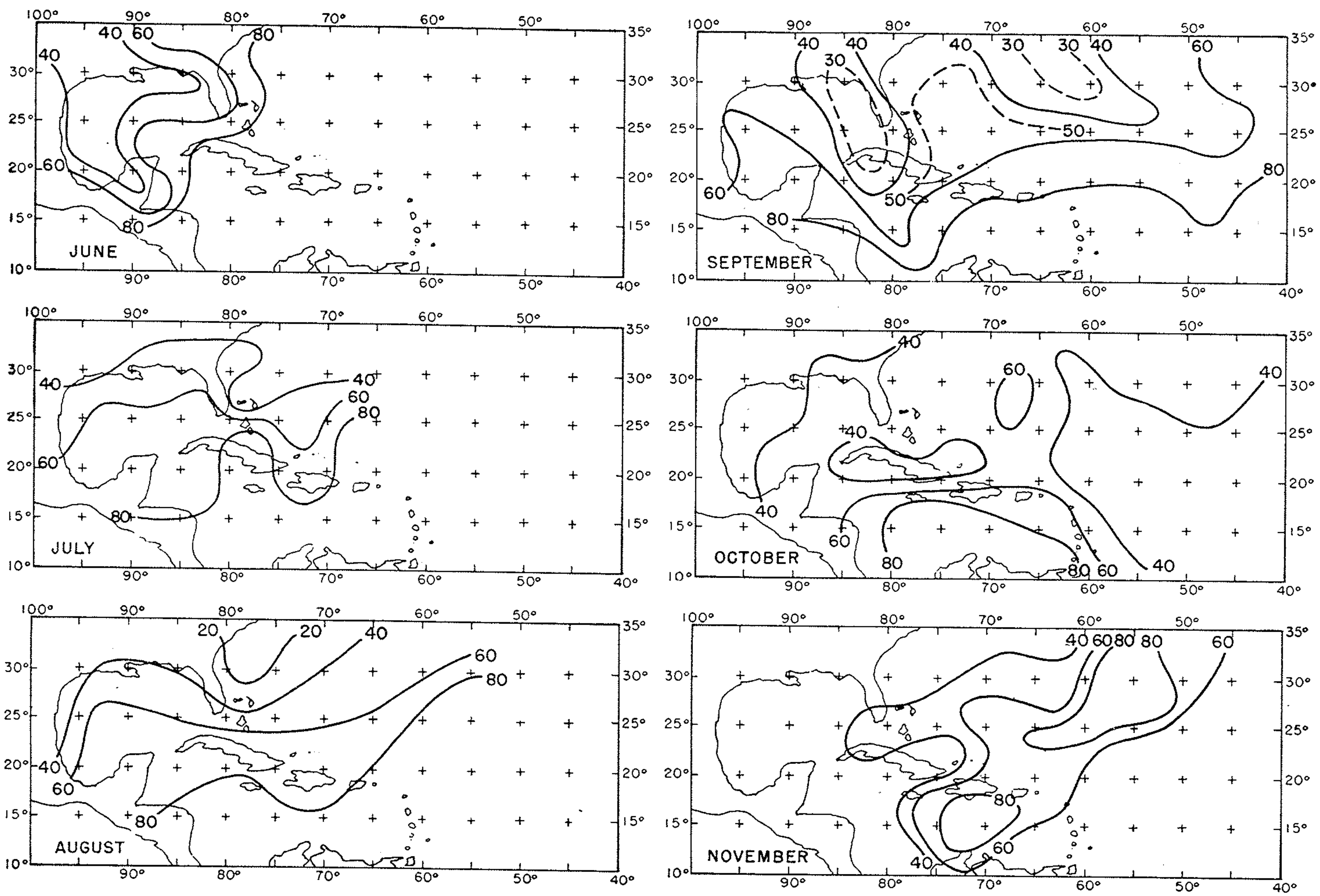


Figure 51. - Percentage frequencies of storms moving on a persistent track. (After Colón [15].)

Also, one could consider persistence of curved paths of storms, but this is generally too difficult to define even with the best storm tracks.

Sea Level Pressure Analysis - The sea level pressure field can be used to forecast the motion of hurricanes, but its usefulness is fairly limited. Generally speaking, hurricanes tend to move along the southern or southwestern boundaries of the subtropical anticyclone, particularly if the atmosphere is quasi-barotropic, which is approximately true south of the subtropical ridge for prolonged periods during the late summer and early fall. A hurricane does not move directly toward a region of high pressure when such an area has stopped moving perceptibly, but moves around the periphery of the high. If, for example, a high hangs persistently over the east coast of the United States, a hurricane will likely be deflected into the Gulf of Mexico before it can turn northward.

In relation to the isallobaric pattern, the same rules of motion that apply to extratropical cyclones also hold for hurricanes. However, 12- or 24-hr tendencies are usually employed in the Tropics in lieu of 3-hr pressure changes, because of the strong diurnal pressure variations. Storms move toward the area of greatest surface pressure fall, provided the change is concentrated within a small area [10]; this indication results in reliable short-term forecasts. Hurricanes also tend to move toward the region where the pressure falls are increasing most rapidly with time. This helps pinpoint the place of entry when the storm is offshore, and is useful for forecasting the motion for periods of 12 hr or less.

Surface Wind Field - Various attempts have been made to use the asymmetry of the surface wind pattern as an indication of the future motion of a hurricane. These have been largely unsuccessful, although Moore [95] developed an equation for the movement of a storm using the winds (based on reconnaissance flights) just above the surface near the east-west and north-south extremities, or outer closed isobar, of a typhoon. This relationship appeared to give good results in the Pacific, but attempts to apply it to hurricanes in the Atlantic have failed to date. This may have been due to the lack of representative reconnaissance wind data near the periphery of the Atlantic storms, and further testing of Moore's techniques is desirable now that aircraft reconnaissance winds are becoming more plentiful.

Since a hurricane moves with the general wind field in which it is embedded, the maximum wind around it should have the same direction as the steering current due to local reinforcement of the two systems. This gives a kinematic basis for the forecasting rule that a vortex tends to move with the strongest wind around it. Since the steering current is small in comparison with the surface winds of a hurricane, however, it is not usually possible to determine the maximum wind with sufficient accuracy to make this rule of much value.

Surface Friction - Very little has been written about the effect of surface friction on the movement of hurricanes, although the increase in friction as a hurricane moves inland is believed to play an important part in changing the direction in which a hurricane moves. Dunn et al [27] attributed a turn to the left by Connie, Diane, and Ione of 1955 to the frictional differential between that portion of the storm over land and the portion over water. Increased friction over land results in a greater cross-isobar flow, which produces an increase of mass and a relative increase of pressure in the right-front quadrant, thus deflecting the center of lowest pressure to the left. As soon as the greater portion of the hurricane, in particular the zone of strongest winds, moves over land the frictional differential decreases and the hurricane resumes its normal course.

The relative importance of surface friction on the motion of hurricanes usually depends upon the speed at which the storm is traveling and whether any new sources of energy are available. A slow-moving storm would be under the influence of this frictional differential for an extended period, whereas the motion of a rapidly moving center should show little change. If the hurricane encounters a new source of energy, the deviation is less pronounced due to increased asymmetry and to acceleration, but usually some brief slowing is still evident.

Clouds - Cirrus clouds usually extend a considerable distance ahead of the storm center, particularly in the direction of the right-front quadrant. The movement of these clouds sometimes gives a good indication of the upper-level current which is steering the hurricane. However, the limitations in the usefulness of cloud movement as a forecast tool should be recognized. If the storm circulation extends to high levels and is discernible over a wide latitudinal range, the clouds will naturally move cyclonically around the storm. On the other hand, the clouds may be observed in the region of outflow within the upper boundaries of the circulation, and in this case the flow will be anticyclonic around the storm. In general, cloud movements are especially significant when a station along the projected path of the storm observes a change in direction, indicating a corresponding change in the steering current.

Interaction of Vortices - The interaction of twin vortices has been the subject of study by both Fujiwhara [32] and Haurwitz [43]. Such a pair of vortices will rotate about a common center, located on a line joining the centers of the two. If

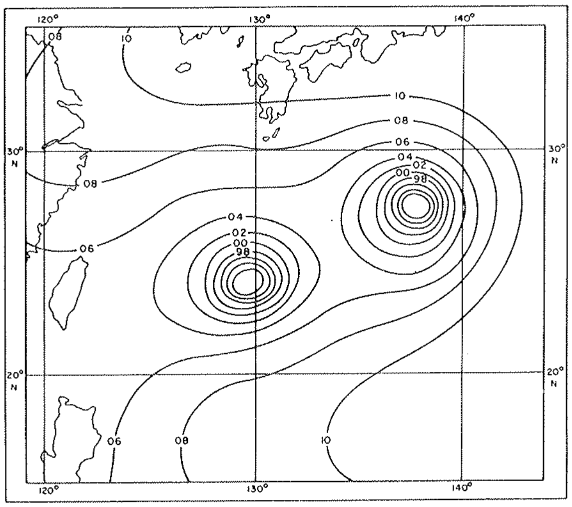


Figure 52. – Sea-level chart for the western Pacific, August 25, 1945. (After Haurwitz [43].)

they are of equal size and intensity, the point of rotation will be midway between them. Otherwise, it will be displaced in reverse ratio to the intensities of the circulations.

Such a vortex pair occurs occasionally over tropical waters. Riehl [125] describes an outstanding example (first studied by Haurwitz [43]) of hurricane pairs, which was observed in the Pacific in 1945 (fig. 52). The two were about the same size, and so they rotated about the midpoint between them. The tracks and that of the midpoint are shown in figure 53 (left). Since the midpoint was moving, it is necessary to subtract its movement from that of the storms in order to obtain their relative motions. Once this is done the interaction is clearly demonstrated (fig. 53, right). The storms rotate about each other and are mutually attracted; as they come closer together, their influence on each other grows and the relative motion increases.

Internal Forces – In a theoretical study, Yeh [163] described an internal mechanism which produces oscillations in hurricane tracks. These oscillations vary in amplitude and period with the size and intensity of the storm, but in the normal range of observed wind fields the amplitude varies from $\frac{1}{2}$ to 2 deg lat with periods of 12 to 48 hr. Prediction of these oscillations is not possible except on a persistence basis, but even this could be important since the size of oscillations would help to determine more precisely where maximum winds might be expected to occur. Also, the use of a persistence forecast could aid in timing oscillations during changes of steering since the oscillations partially determine how the storm will react to the new current. More studies must be conducted on this subject before these oscillations can be used by the forecaster with any degree of confidence.

Another significant internal force is the poleward acceleration of a hurricane associated with variations in the Coriolis parameter across the latitudinal breadth of the storm [130]. Although this acceleration is rather small as a rule and difficult to measure, significant portions of total hurricane displacement can be attributed to it in certain cases, as shown by Cressman [20]. This northward drift of tropical cyclones has been noted for some time and is illustrated quite clearly in the regression equation of Riehl et al [127] for northward motion (see equation 1 below), which shows that storms move northward at an average rate of 0.8 deg lat/day when the geostrophic steering current is zero. Since this effect is greater the larger the storm, it is not surprising that large storms have been observed to drift northward as

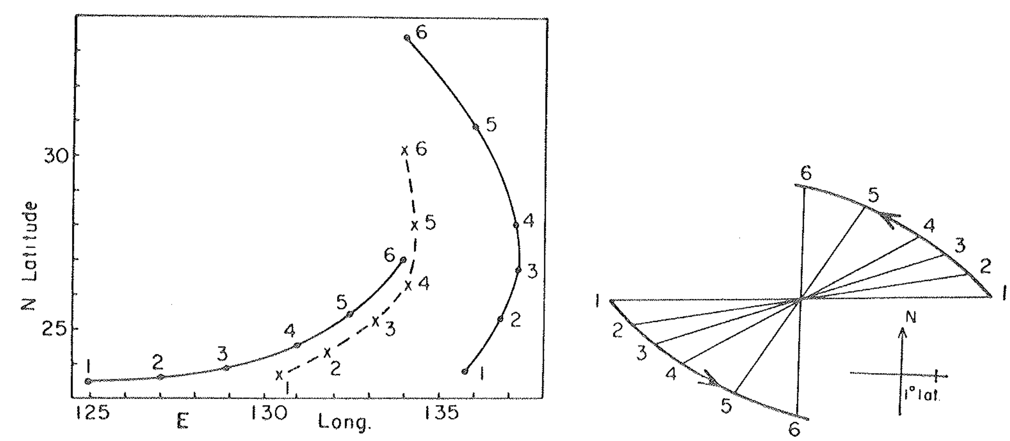


Figure 53. – Left: Tracks of typhoons of figure 52 (solid) and center of rotation (dashed) for six 12-hr intervals beginning August 24, 1945. Right: Relative motions of typhoons. (After Riehl [125]; by permission of McGraw-Hill Book Co., Copyright 1954.)

much as 1 to 2 deg lat/day even if there is no steering current aloft [125].

Tides and Swells - The generation of swells by a hurricane is very complex due to the curving wind flow [25]. Waves move with the winds which create them, and as a result, swells move out from the storm in all directions. Those generated by the right half, however, move under the influence of winds which change little in direction for a longer period of time. These eventually travel a great distance ahead of the storm, and have some forecast value.

If the direction of the swells remains constant, the center of the storm is either approaching or going away from the observer. If their direction changes counterclockwise, the center is passing from the observer's right to his left. If the swells change clockwise, the center has passed or is passing from left to right. The direction from which the swells approach the observer indicates the direction of the storm at the time the swells were generated.

Tides, particularly in the Gulf of Mexico, also have some forecast value. Abnormally high tides indicate the presence of a storm. An area along the coast where the tides exceed the normal and continue to rise is generally in line with the advance of the storm. If the point of greatest positive departure from normal shifts right or left, this indicates that the storm is changing direction toward the point where the greatest rise is taking place.

Steering by Upper Flow Patterns

Basis of Steering Concept - The movement of a tropical cyclone is determined to a large extent by the direction and speed of the basic current in which it is embedded. Much of the emphasis in hurricane forecasting has been directed toward an evaluation of this basic or "steering" current. Over the years a number of short-range forecast methods have been developed which make use of various concepts of steering and although some have generally given good results, there are serious failures at times.

A number of difficulties are apparent both in determining just what is the basic current and in relating this precisely to storm movement. The storm circulation, being extensive both horizontally and vertically, obscures the basic current over a considerable area. If it is determined what the undisturbed flow would be, there still exists the question of what part of the motion is due to the actual carrying along of the storm by this current, which has been called the "convective" component of the velocity of propagation, and what part represents the "dynamic" component which is due to asymmetry in the field of horizontal divergence. Sherman [140], in an analysis of a limited number of cases for which wind data were available at the time, tentatively concluded that the computed convective velocity accounted for only a little more than half of the observed variability in direction of propagation and that the dynamic component is likely to be significant. The "steering" methods rely heavily on the influence of the basic current on the storm's movement although most of them, being empirically derived, doubtless incorporate to some extent the average "dynamic" component of the velocity of those storms which were used in developing the techniques.

E. Jordan [69] found support for the idea of a steering current in an analysis of winds between 4000 and 30,000 ft located between 2 and 4 deg lat from the center of a considerable number of storms. She considered the circulation to be a combination of a field of rotation and a field of translation and concluded that, within the limits of observational accuracy, the field of translation, or steering current, agreed with the movement of the storm. The steering current in this case was defined as the pressure-weighted mean flow up to 300 mb extending over a band 8 deg lat in width centered over the storm. Further investigation of this relationship between storm movement and upper-level winds by Miller [86] indicates that for moderate and intense storms the best hurricane steering winds are to be found in the layer between 500 and 200 mb and averaged over a ring extending from 2 to 6 deg lat from the storm center.

Practical applications of the steering concept to short-range hurricane motion use differing approaches in attempting to measure the basic current. One is by streamline analysis of successive levels to find a height at which the vertical circulation diminishes to a point such that the winds are supposedly representative of the undisturbed flow. A second method is to take vector averages of reconnaissance winds near the zone of strongest winds in the storm. Another method commonly used in the absence of adequate wind data is the computation of geostrophic components of the mean flow at 500 mb or at other levels, taking measurements at a sufficient horizontal distance from the center to avoid the more active circulation of the storm.

Use of Observed Winds Aloft for Steering - When sufficient data are available it has been found that the use of streamline analysis of successive levels usually gives valuable indications of tropical storm movement for as much as 24 hr in advance. Since wind observations are usually scarce in the vicinity of a hurricane, their analysis must be rather subjective. However, Norton [109] claimed success in using this concept and said that it seldom failed to give dependable results when data were available to high levels near the storm. The technique is not based on an assumption that the wind at any single level is responsible for steering the storm since the forces controlling movement obviously act through a deep layer of the atmosphere. However, as successive levels are analyzed, a level is found at which the closed cyclonic circulation of the storm virtually disappears. This "steering level" coincides with the top of the warm vortex and varies in height with different stages and intensities of the hurricane. It may be located as low as 20,000 ft, or in a large mature cyclone as high as 50,000 ft.

In the absence of sufficient data to determine the level at which the cyclonic circulation vanishes, it is sometimes possible by streamline analysis based on surrounding data to decide at which level the direction of the flow corresponds with the past or present movement of the hurricane. It has been found in this analysis that the most weight should be given to the winds in advance of the storm within a radius of 200 to 300 miles in preference to those in the rear quadrants. The hurricane generally moves with a speed of 60 to 80 percent of the current at the steering level.

The direction of movement is not always exactly parallel to the steering current but may have a component toward high pressure which varies inversely with the speed of the current, ranging from almost zero deg with rapid movement to as much as 20 deg with speeds under 20 kt. In westward moving storms, a component of motion toward high pressure could result from the poleward acceleration arising from variation of the Coriolis parameter across the width of the storm, an effect which was mentioned above. This would indicate that, to the extent that this effect accounts for the component of motion toward high pressure, northward-moving storms would fit the direction of the steering current more closely than westward-moving ones. The tendency for poleward drift would be added to the speed of forward motion in case of a northward-moving storm so that it would approach more closely the speed of the steering current. Empirical evidence supports this hypothesis.

Corrections for both direction and rate of movement should be made when this is indicated by the wind flow downstream in the region into which the storm will be moving. It is apparent that for prediction beyond several hours, changes in the flow patterns for a considerable distance from the hurricane must be anticipated. It should also be remembered that intensification or decay of a storm may call for the use of a higher or lower level, respectively, to estimate the future steering current.

Another approach to the use of observed upper winds for predicting storm motion has recently been made by Gentry [35]. He has found that mean resultants of winds measured by reconnaissance aircraft at a single level in each of the four quadrants of a hurricane are related to succeeding 24-hr motion of the storm. Resultants were computed at radii varying from 30 to 100 naut mi about the center of the storm and at levels from 700 to 250 mb. Best results were found for winds measured at a radius slightly greater than the radius of maximum winds in the storm. The predicted motions using these resultant upper winds were almost without exception better than persistence (continuity) and also gave better estimates of motion in the future 24 hr than they did for current motions of storms. However, these findings were derived from a very limited sample of storms, so that further testing is necessary before the method can be incorporated in routine forecast procedure.

Use of Geostrophic Winds for Steering - The expansion of the upper-air network and the availability of supplementary data from aircraft reconnaissance have made it practical to carry out more detailed analyses of constant pressure surfaces over the hurricane belt and make use of a forecast method based on geostrophic components at that level. Such a technique developed by Riehl, Haggard, and Sanborn [127] has shown promising results. This technique makes use of 500-mb heights averaged along sides of a rectangular grid approximately centered on the hurricane. After experimentation with larger grids it was found that the best grid size was 15 deg long centered at the initial longitude of the storm and between 10 and about 15 deg lat with the southern end fixed at a distance 5 deg lat south of the latitude of the storm center. The more northward extension of the grid is used for storms found to be moving more rapidly northward. The relatively small grid size indicates that hurricane motion for 24 hr is determined to a great extent by circulation features closely bordering the storm and that, on the average, features outside this area will not greatly affect its movement within this time interval.

These average geostrophic wind components were obtained for a sample of cases and correlated with observed 24-hr displacements. The following regression equations were obtained:

$$C_n = 0.8 + 1.2\, G_n \qquad (1)$$

for northward motion,

$$C_w = G_w \qquad (2)$$

for westward motion, and

$$C_w = 0.96\, G_w + 0.02\, G_w^2 \qquad (3)$$

for eastward motion; where C_n and C_w are the

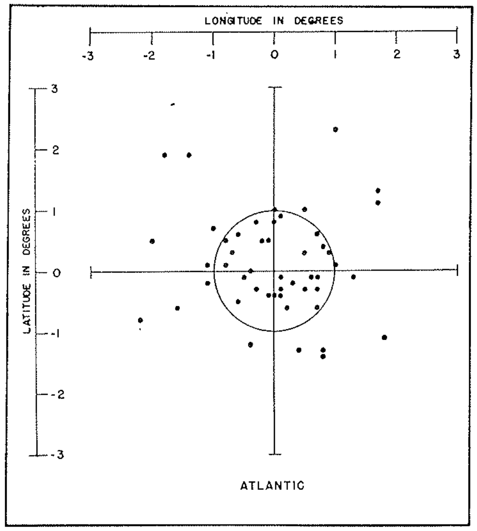


Figure 54. - Error distribution of 24-hr forecasts made from current charts at Project AROWA during 1955 hurricane season using geostrophic component steering method. Each forecast position of a storm center is shown by a dot relative to the observed position at the origin. (After Riehl, Haggard, and Sanborn [127].)

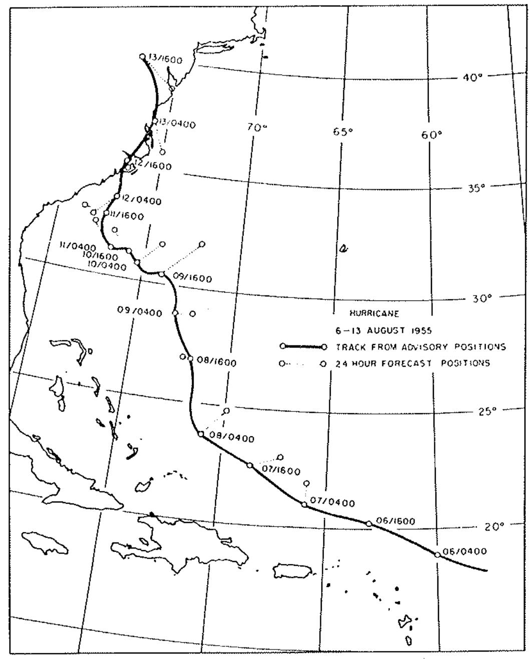


Figure 55. - Track of hurricane Connie, August 6-13, 1955, and 24-hr predicted positions using geostrophic component steering method. Dashed lines show forecast errors. (After Riehl, Haggard, and Sanborn [127].)

northward and westward components of storm motion respectively, G_n and G_w are the corresponding 500-mb geostrophic flow components. The units of (1) are deg lat/day; those of (2) and (3) are deg long/day. From these equations it can be seen that the 500-mb current as measured in this method fully approximates the storm motion during westward motion, but storms moving eastward (C_w and G_w negative) move somewhat slower than the 500-mb steering current, particularly for stronger westerly geostrophic flow. The northward movement of storms is more rapid than the geostrophic components. This has been attributed by Riehl et al [127] to the internal forces which produce a poleward displacement of cyclones, but it could also be due to systematic increases in east-west height gradients which may occur at the time storms are moving northward, or to the fact that the steering level may be higher than 500 mb for storms moving northward.

For the original test samples, storm positions predicted by this method verified within 1 deg of longitude and latitude in 70 to 80 percent of the cases. A test of the method by Project AROWA during the 1955 Atlantic hurricane season (an independent sample), gave slightly poorer results, however, with just 65 percent of the predicted positions located within 1 deg of longitude and latitude of the observed locations. This distribution of predicted storm positions relative to the observed is shown in figure 54. Verifications of

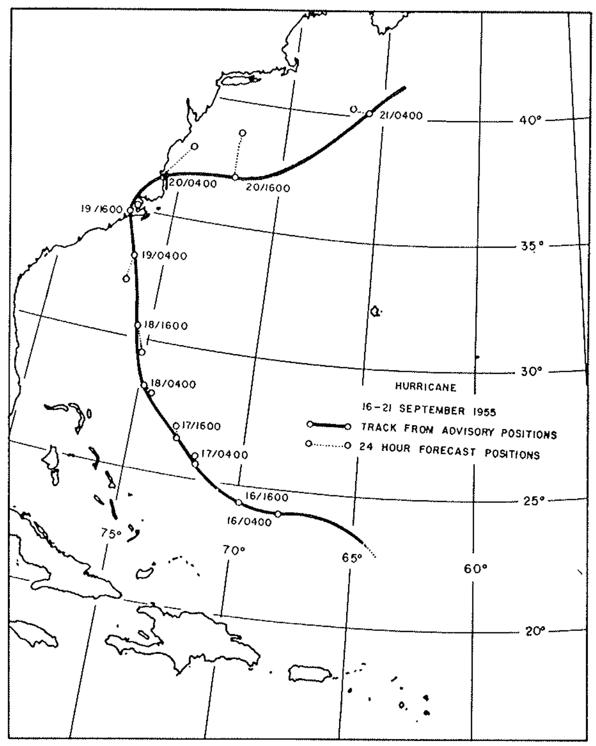


Figure 56. - Track of hurricane Ione, September 16-21, 1955, and 24-hr predicted positions using geostrophic component steering method. Dashed lines show forecast errors. (After Riehl, Haggard, and Sanborn [127].)

the method for two particular cases in 1955 are shown in figures 55 and 56. Tests of this method under actual operating conditions at various forecast centers for a limited number of cases showed an average error of 119 naut mi in the 24-hr forecast position. It is significant that variations between the average errors obtained at different centers were frequently of about this same magnitude. Since the technique is basically objective once a 500-mb analysis is available, these differences indicate that the skill of the method is highly sensitive to variations in analyses of the 500-mb chart from one station to the next. This emphasizes the need for better data coverage, but even with the present data it points to the necessity for as careful an analysis of the 500-mb chart as possible by making the fullest utilization of all data at 500 mb as well as at other levels (sea level in particular). Admittedly this is a difficult task on an operational basis since all significant data may not be available by the time the forecast must be issued. An example of the actual application of this method is given in Appendix I.

In an effort to devise a method for predicting 36-hr hurricane motion, a group at the National Hurricane Research Project [107] made use of geostrophic components of the mean flow between 850 and 300 mb to obtain first approximations to the east-west and north-south components of the hurricane's motion. The grid used for obtaining the geostrophic steering current was basically similar to that used by Riehl et al [127] and also in similar fashion regression equations were obtained between observed (36-hr) storm travel and geostrophic steering wind in each direction. It was found that the components in the zonal direction could be estimated with more accuracy than those in a meridional direction. Since it is realized that significant changes in the basic steering current can occur due to changes in circulation not only in the subtropics, but also in the middle-latitude westerlies, attempts were made to correct these first calculations by assessing the state of the westerly circulation to the northwest of the storm center by means of a secondary grid system.

After some experimentation it was found that the calculations in the north-south direction could be improved most by considering changes in the magnitude and direction of the mean resultant (geostrophic) wind vector in a rectangular grid area (10 deg lat by 15 deg long) centered 10 deg lat north and 30 deg long west of the hurricane center. East-west components were improved somewhat by considering changes of a mean resultant wind in a similar rectangular grid centered 10 deg lat north, but only 15 deg long west of the storm. For the dependent data used in this study the average error for 36-hr predictions in the zonal direction was 105 naut mi and in the meridional direction 84 naut mi, or a total mean error of 134 naut mi. Sufficient tests of the method on independent data are not as yet available.

One interesting by-product of this study was an evaluation of the individual versus the joint contributions of the 850- and 300-mb levels in steering the hurricanes. It was found that the best forecast of the zonal motion of the storm could be obtained from data at 850 mb alone. On the other hand, the meridional motion was best related to data at 300 mb modified by the shear of the meridional geostrophic components between 850 and 300 mb.

The Influence of 500-mb Height Changes on Storm Motion - In the study just described, it was found that predictions obtained from steering components could be improved by considering changes in the westerly flow pattern at some distance to the northwest of the hurricane. Such effects have also been emphasized by Hoover [52], who studied in some detail the relationships between 24-hr changes in 500-mb height and changes in the direction and speed of hurricanes. Although he presents only qualitative evidence of these influences it is quite clear that they must be considered in applying any steering method to a particular situation where sizeable changes in height are occurring (outside the area immediately surrounding the hurricane). A diagram of Hoover (fig. 57) illustrates the influences that some typi-

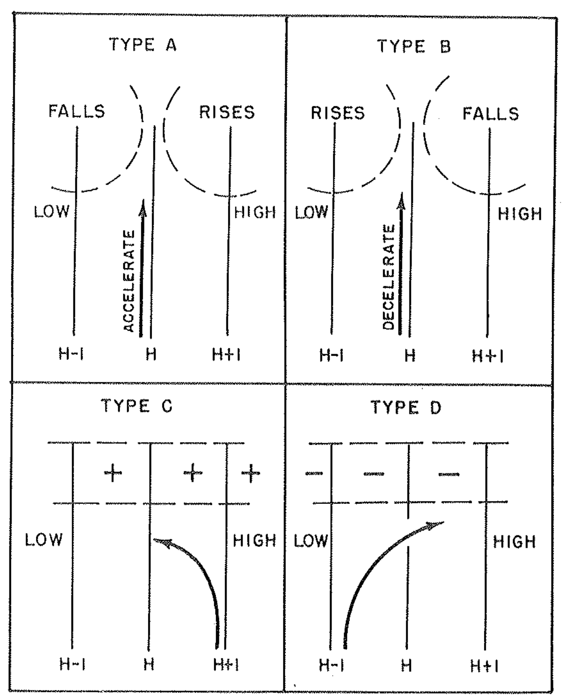


Figure 57. - Illustrations of the effects of 500-mb 24-hr height changes on hurricane motion. Tracks of storms indicated by heavy arrows. (After Hoover [52].)

cal change patterns would have on the storm's motion. Types A and B are cases where the changes would act to reinforce or weaken the initial steering current, thereby resulting in a speedup or slowdown in the storm without change of direction. In types C and D rises or falls lying solidly in the path of the storm, would act to deflect the storm to the left or right, respectively, of its initial direction of motion.

Thermal Steering - A number of efforts have been made to correlate hurricane movement with thermal patterns. When a storm is in an area where accurate 500- and 700-mb charts can be prepared, Simpson [142] has suggested that it is possible to relate its movement to thickness patterns between these surfaces in fairly systematic fashion. This is based on the assumption that when the storm is moving, warm air in the layer 700 to 500 mb extends as a tongue ahead of it and the orientation of the axis of the tongue may be regarded as a reliable indicator of storm movement for the next 24 hr. The tongue is at times displaced to the right of the path of the storm and in this case the indicated movement is parallel to the major axis of the warm tongue. Since thickness is directly proportional to the mean virtual temperature of the layer, isopleths of height difference between 500 and 700 mb, drawn for 100-ft intervals, are used to delineate the warm tongue. A considerable difficulty in applying this technique, however, is created by the fact that the warm tongue sometimes has more than one branch and it is questionable as to which is the major axis. An example of the usefulness of Simpson's method of warm tongue steering is given in Appendix II.

There have been a number of other attempts to correlate hurricane movement with thermal patterns. Kamiko [71] found that there were greater vertical instabilities in the external region of tropical storms, particularly in the direction of motion. Research by Okubu and Nakamura [111] indicated that the temperatures of the stratosphere were significant in determining typhoon movement; i.e., a storm moves toward a cold stratospheric area, or along a cold trough, and avoids a warm area, which may appear in its path, by shifting direction or filling. Unfortunately, lack of data has handicapped the testing and application of these various ideas based on thermal patterns; so their usefulness is purely subjective at the present time.

One method which is quantitative and has been subjected to limited testing, however, is a prediction method devised by Muench [96]. He has related hurricane motion to a "thermal trajectory", which is the vector difference between geostrophic steering computations made from spatially smoothed charts at sea level and at 500 mb. Statistical relationships were obtained between the actual motion and this thermal trajectory for cases during three hurricane seasons (1952-1954). Application of the method to independent data for three hurricanes in 1955 gave an average error of 89 naut mi in predicted 24-hr storm position. Some other tests with Muench's method have not yielded as good results. It was found in particular [107] that it was unsatisfactory for westward-moving storms.

Statistical Methods

Several of the short-range techniques already discussed are at least partly statistical. In this section, however, two recently derived methods which are virtually purely statistical, will be discussed.

The first of these methods is one devised by Veigas and Miller [157] to predict 24-hr displacement of hurricanes based primarily on the latest sea-level pressure distribution. This dependence on sea-level pressures rather than upper-air data is due primarily to the longer available record of sea-level data, but also there are other advantages such as denser areal and time coverage and more rapid availability of the data after observation time. In addition to the sea-level pressure field, the method also incorporates past 24-hr motion of the storm and climatological aspects of the motion.

In this study a total of 447 cases of hurricanes and tropical storms on the 1230 GMT maps during the years 1928-1953 constituted the sample from which multiple regression equations were derived for 24-hr storm motion in two geographical zones shown in figure 58. A 5 deg lat-long grid with a total of 91 pressure values was used to relate the sea-level circulation pattern to the subsequent hurricane position. This grid extended over a lati-

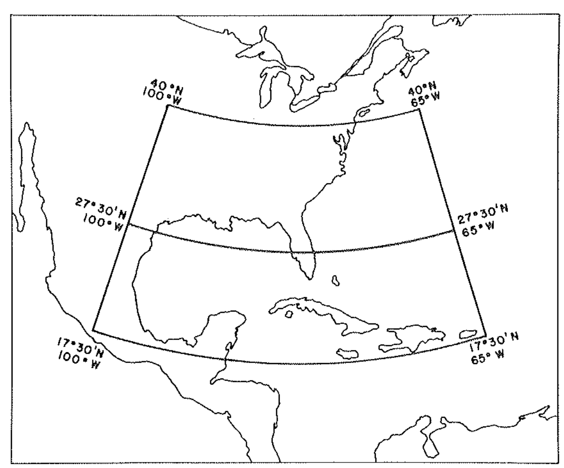


Figure 58. - Northerly and southerly zones within which the hurricane must be located at forecast time in Veigas-Miller statistical prediction method. (After Veigas and Miller [157].)

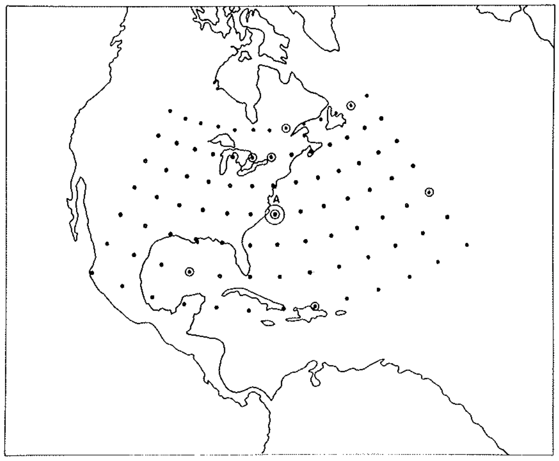


Figure 59. - Pressure grid for northerly area (see fig. 58). Point A is grid point nearest the hurricane center at forecast time. Sea-level pressure values at circled points are used in regression equations for u or v components of storm motion. (After Veigas and Miller [157].)

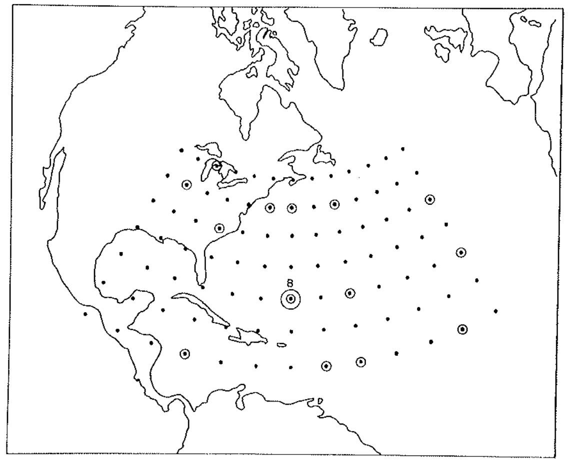


Figure 60. - Pressure grid for southerly area (see fig. 58). Point B is grid point nearest hurricane center at forecast time. Sea-level pressure values at circled points are used in regression equations for u or v components of storm motion. (After Veigas and Miller [157].)

tudinal distance of 30 deg and a longitudinal distance of 60 deg, centered at the grid point nearest the hurricane center for storms in the northerly zone, and centered 5 deg lat north of the grid point nearest the hurricane center for storms in the southerly zone. Examples of the grid location for storms centered near Hatteras and northeast of the Antilles are shown in figures 59 and 60, respectively.

For each of the cases in the developmental sample there were 95 variables available. These were the 91 grid pressure values, two coordinates for storm position at prediction time, and two coordinates for storm position 24 hr prior to prediction time. From this large set of possible predictors a multiple linear regression procedure was used to select a smaller group of predictors which contributed significantly and independently to storm motion. This is the so-called screening procedure which is described qualitatively by Panofsky and Brier [116] and mathematically by Veigas and Miller [157]. This screening procedure was performed by means of an IBM 704 computer. For each geographical zone two prediction equations (one for predicted longitude, the other for predicted latitude) were derived. Each equation contains as predictors the current and preceding (24 hr earlier) longitude and/or latitude of the storm plus two to eight sea-level pressure values. The circled grid points in figure 59 show the pressure values that enter the prediction equations (including the pressure value at the storm's center - point A) for storms in the northerly zone. Similarly, for the southerly zone the pressure values entering the prediction equations are circled (including the pressure at the grid point nearest the storm's center - point B) in figure 60. The equations and a detailed example of their application to an actual hurricane are given in Appendix III.

This method was tested by Veigas and Miller [157] on 125 independent cases, about equally distributed between the two zones, during the years 1924-1927 and 1954-1956. The average vector errors in 24-hr forecast position were 150 naut mi in the northerly zone and 95 naut mi in the southerly zone.

Examples of predictions made at 24-hr intervals for two hurricanes in this independent sample, Betsy and Flossie of 1956, are shown in figures 61 and 62. These were generally good forecasts, with errors for Betsy ranging from 25 to 120 naut mi and those for Flossie ranging from 50 to 100 naut mi. It is noteworthy that the method successfully caught the recurvature of Betsy, which occurred between August 15 and 16, and also some of the accelerations of both storms. On the basis of the independent sample in general, the method does appear to have the ability to forecast acceleration, deceleration, and recurvature. However, the method made most of its biggest errors in handling rapid accelerations of storms transforming to extratropical cyclones.

Another statistical method for predicting 24-hr hurricane motion has recently been developed by Jorgensen [70]. This method makes use of predictors based on 500-mb height data as well as sea-level data, continuity, and climatology of motion. However, the developmental data were much more restricted than those used by Veigas and Miller. Jorgensen's data consisted of 67 fore-

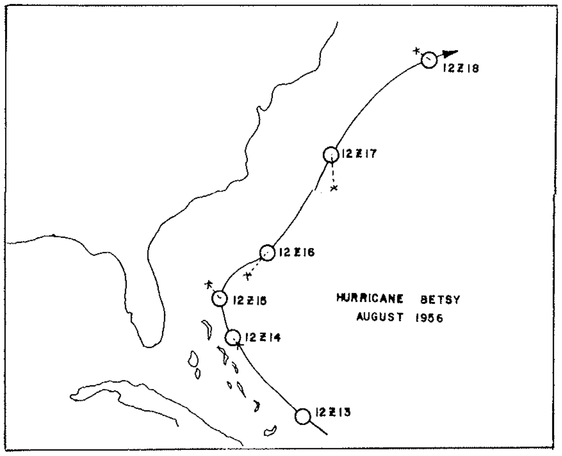


Figure 61. - Predicted positions (crosses) of hurricane Betsy, August 1956 using Veigas-Miller method. Observed positions are indicated by circles. Dashed lines show forecast error. (After Veigas and Miller [157].)

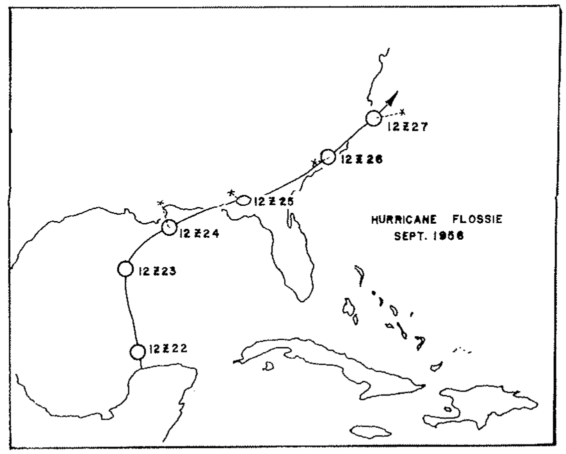


Figure 62. - Predicted positions (crosses) of hurricane Flossy, September 1956 using Veigas-Miller method. Observed positions are indicated by circles. Dashed lines show forecast error. (After Veigas and Miller [157].)

cast cases selected from the period 1951-1955 and and only from those storms initially located north of 30°N and west of 65°W (into the eastern United States). 500-mb heights and sea-level pressures were considered over a rectangular grid extending 10 deg lat south of the initial storm location and 14 deg lat or long north, east, and west of the center. Instead of using height and pressure data directly, the height and pressure patterns were fitted with orthogonal polynomials, whose use is explained by Malone [84]. (The polynomials are used primarily to reduce the number of parameters needed to describe the height or pressure pattern.) The coefficients of these polynomials, which represent various constituents of the flow patterns at 500 mb and sea level, were correlated with storm motion.

After investigating the relationships of 28 parameters to storm motion, Jorgensen chose the 9 best predictors for each component of storm motion (i.e., north-south and east-west). For the north-south component of motion it was found that the best of the nine predictors were persistency (continuity) and a polynomial at 500 mb which measures the strength of a ridge to the east of the storm and a trough to the west. The next two predictors of some significance were two sea-level polynomials. For the east-west component of motion the best parameters were a polynomial at 500 mb measuring the overall strength of the westerlies in the grid and persistency of motion.

Tests of this method on independent data, 45 forecasts for storms in 1949, 1950, 1955, 1956, gave a mean vector error of 135 naut mi, which is a somewhat smaller error than obtained by Veigas

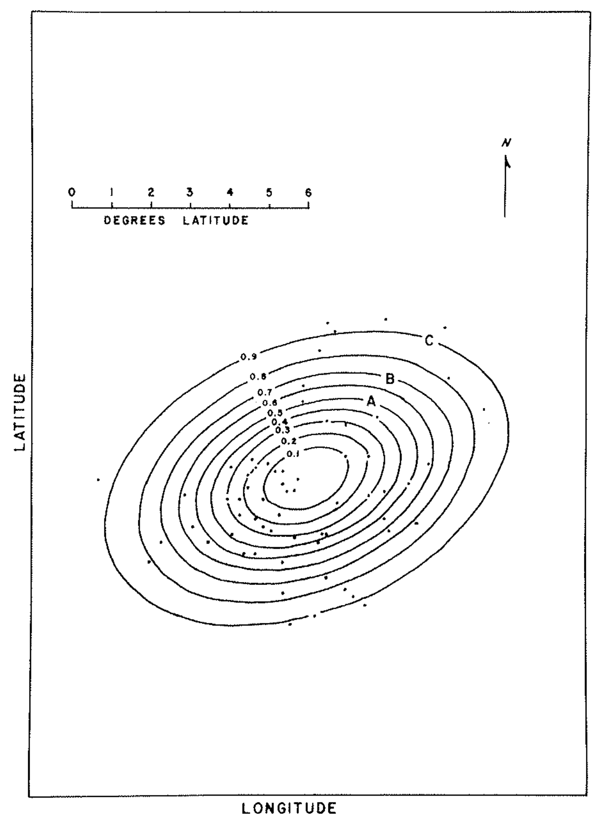


Figure 63. - Distribution of vector errors for 65 independent predictions by Veigas-Miller method for northerly zone. The origin represents the forecast position and each point is the observed position relative to the forecast position. Ellipses A, B, and C enclose the areas which should include 50, 70, and 90 percent of the cases, respectively, assuming a bivariate normal distribution of the u and v components of the vector error. (After Veigas and Miller [157].)

and Miller in their northerly zone. A more detailed explanation of this method and an illustration of its application in predicting the motion of a given storm are given in Appendix IV.

In both of these statistical studies the forecast storm positions were analyzed in terms of their locations relative to the observed storm positions. The distributions of these positions form elliptical patterns such as those shown in figure 63. The set of elliptical contours can be used to estimate the probability of the actual storm position falling within given distances of the predicted position. This type of analysis can be performed for any forecasting method and the probabilities of the prediction being correct within certain limits of error can serve as useful guides in deciding what the likelihood is that certain areas may be closer to or farther away from the storm center than predicted.

Numerical Prediction Methods

Hurricanes and other tropical cyclones have appeared on routine prognostic charts produced by the Joint Numerical Weather Prediction Unit (JNWP) since the 1955 hurricane season. The barotropic and baroclinic models used by JNWP [147] are rather general models which were not specifically designed for small systems like the tropical cyclone. Nevertheless since these prognoses are routinely available to forecasters, a study was undertaken by L. Hubert [56] to evaluate their performance in prediction of hurricane motion. In order to accumulate a modest sample of hurricane data, numerical barotropic forecasts were made for seven major hurricanes in the period 1951-1954 and these forecasts, along with those for the storms of 1955, were verified.

It was found that the barotropic forecasts generally underestimated the motion of the storms. For example, the 24-hr forecasts had an average vector error between predicted and observed storm positions of 140 naut mi while the error for 48-hr forecasts was twice as big. For both periods the mean predicted storm position was almost directly to the rear of the storm's actual position. This is primarily indicative of the slowness of the forecast, but it also demonstrates that the forecasts had no bias in predicting the storm's direction of motion; i.e., the predicted track deviated to the left of the observed path just about as often as it deviated to the right. There was a good deal of scatter of individual predicted storm positions about the mean predicted position. For example, the 24-hr forecast positions had a standard deviation of 139 naut mi from the mean position. In general then the conclusion from this study was that these numerical forecasts of hurricane motion were not good enough on the average to be operationally useful.

These poor results appear to be mainly attributable to certain deficiencies of the model used in the computations. One of the major sources of error as far as the hurricane is concerned is truncation error, which is the error made in approximating continuous derivatives of the height field by their finite difference equivalents. In the particular model used for these forecasts the spacing between grid points (about 260 naut mi at latitude 30°) was often too large relative to the usual hurricane circulation. In fact the geostrophic wind components used in advecting vorticity were calculated from height differences between points two grid intervals apart (approximately 520 naut mi). In this situation a relatively small difference in position of a hurricane relative to one or more of these geographically fixed grid points could cause huge variations in the computed vorticity of the storm, as well as its carrying current. Another related effect of the large grid is that the storm center cannot be uniquely located from the data at the grid points owing to the asymmetry of the height field surrounding the storm. Thus, it was found that even if one made a perfect forecast an average error of about 70 naut mi might be expected in estimating the position of the storm center from the predicted heights at the grid points. The smaller grid (about 165 naut mi at latitude 30°) now used in the barotropic model may reduce these errors somewhat, but it is doubtful that this reduction in grid size would be sufficient to bring about a significant improvement in hurricane forecasts using the barotropic prognostic charts. Limited barotropic experiments by Birchfield [7], using a fine grid spacing of about 80 naut mi, indicate that some improvement may be achieved by further reduction of the grid size, provided that quite adequate wind and pressure observations about the storm are available.

Other errors in these routine forecasts may have resulted from the general inadequacy of the barotropic model in predicting changes in 500-mb heights near the hurricane. There are many problems such as the use of the geostrophic assumption (or even the somewhat better estimate of the winds and vorticity from the height field now used in the operational models), the assumption of no divergence at 500 mb, and the neglect of other terms in the vorticity equation. Even some of the baroclinic models used by JNWP, such as the three-level baroclinic (in routine use through June 1956) and the thermotropic (in routine use between July 1956 and October 1957), would not be especially good for hurricanes since they make assumptions which would be very poor for the tropical cyclone. One of the most damaging assumptions, for example, is that the flow is adiabatic. Thus, these models would have no way of handling the effects of the latent heat of condensation, which is believed to be of utmost importance in the hurricane's maintenance and development and in its effects on its environment. However, models taking into account heat of condensation are being developed (e.g. [2] and [144]) and may become operational in the not too distant future. Other problems of numerical forecasting which may have also contributed to the poor results are boundary errors (the boundary of the forecast area was across the southern Caribbean and not far east of the Antilles) and poor 500-mb data coverage near the storms.

Meanwhile, as an interim approach to numerical prediction of hurricane motion, there have been some efforts to use barotropic forecasts in a selective fashion to estimate and predict the broad steering current in which the storm is located and hence predict the storm's trajectory. In view of the moderate success of the method of Riehl, Haggard, and Sanborn [127], which is based on the latest observed 500-mb heights (but with empirical corrections), it is logical to assume that a steering technique which also takes into account the expected changes in the height field should be even more successful. It has been demonstrated [57, 66] that the barotropic model does a fairly satisfactory job of predicting 500-mb heights in the subtropical Atlantic, except for the regions in the very immediate vicinity of tropical storms. Thus, the numerically predicted heights could be used to obtain a prediction of the steering current and trajectory of the storm.

An early attempt along these lines was made by Sasaki and Miyakoda [131] who subtracted the vortex circulation of the typhoon or hurricane from the observed 700-mb height field and then predicted its track by means of the residual circulation pattern (i.e., steering current). Numerical prediction of this residual circulation pattern was accomplished by the Fjørtoft graphical method with time steps of 12 hr. A similar experiment using 12-hr time steps to obtain the predicted hurricane trajectory was tried by L. Hubert [56]. He did not remove the storm circulation, but simply measured the geostrophic steering current by taking height differences over distances of 10 deg lat and 15 deg long centered on the storm. The predicted trajectory was constructed assuming uniform motion with the initial steering current for a 6-hr period subsequent to the initial map and then with the predicted steering current for 12-hr periods centered on each prognostic map. Forecasts by this method proved to be no better than the regular barotropic forecasts described earlier. Apparently

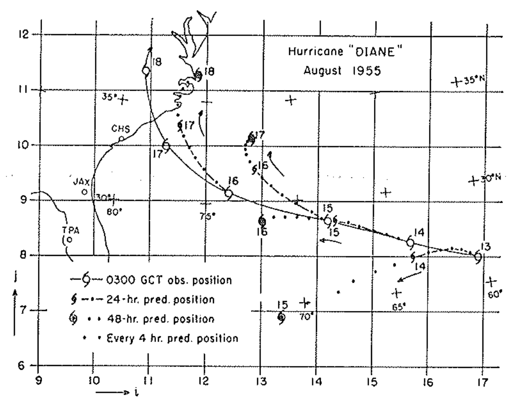


Figure 64. - Numerically predicted 48-hr trajectories of hurricane Diane, August 1955, as compared with observed track. Dated hurricane symbols show positions (forecast and observed) for 0300 GMT. General trend of 48-hr predicted trajectory is shown by curved arrow. (After Kasahara [72].)

this particular approach was too crude to overcome some of the basic difficulties associated with the barotropic model.

More refined methods, in which the trajectory of the tropical storm is predicted by using the wind field at each time step in a barotropic forecast computed by electronic machine, have been developed by Kasahara [72, 73] and W. Hubert [60]. In the first of these methods a procedure similar to that developed by Sasaki and Miyakoda [131] was applied at both 500 mb and 700 mb, using time steps of one hour, to the cases of hurricanes Connie and Diane of 1955. The entire series of 24-hr forecasts for these two storms reported in [73] had an average vector error of 100 naut mi using either 500 or 700 mb as the forecasting level. The 48-hr predictions had vector errors of 260 and 230 naut mi for 500 and 700 mb respectively. Predictions made for hurricane Diane using 500-mb data are illustrated in figure 64.

It is interesting to note that by taking a combination or average of the forecasts at each level Kasahara obtained significantly better results. These so-called "resultant" forecasts had an average vector error of only 70 naut mi for 24 hr and 200 naut mi for 48 hr. These results indicate that the use of a vertically averaged steering flow in the barotropic model may produce forecasts more reliable than the use of flow at only a single level.

In W. Hubert's [60] method a cubic equation is fitted (using the electronic machine) to the height field at 16 grid points (a four by four square) surrounding the storm. (The grid spacing is about 165 naut mi at latitude 30°.) Thus 500-mb height becomes a function of the x and y coordinates, and

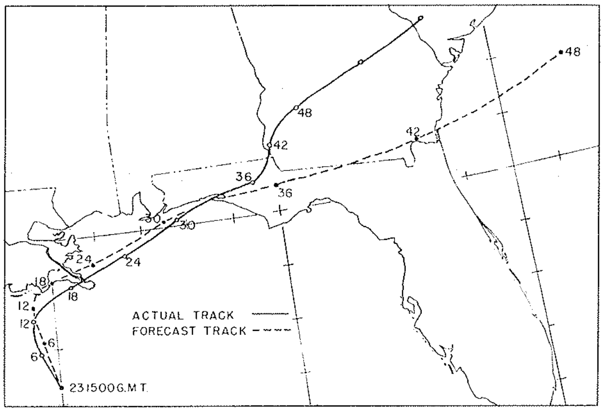


Figure 65. - Numerically predicted path of hurricane Flossy (dashed) for 48 hr starting at 1500 GMT, September 23, 1956 as compared with observed track (solid). Numerals indicate forecast and observed positions at various hours from forecast time. (After Hubert [60].)

can be expressed as

$$Z = A+Bx+Cy+Dx^2+Ey^2 + Fxy+Gx^3+Hy^3+Ix^2y+Jxy^2, \quad (4)$$

where the coefficients are derived from the height field. This expression can be differentiated to obtain the partial derivatives, $\partial Z/\partial x$ and $\partial Z/\partial y$, which are needed to obtain the geostrophic wind components. The derivatives are evaluated for the storm center by substituting the proper x and y coordinate values at which the storm is located in the grid. The storm is then moved with this computed current for one time step (one hour). At the next time step the barotropic forecast has changed the height field so that a new cubic equation must be fitted to the heights in the four by four grid. (Different grid points are used if the storm moves out of the center box of the original grid.) The derivatives are obtained again in the same manner and a new steering current at the storm's center is calculated. This procedure is iterated until a complete trajectory forecast for any desired time interval, such as 12, 24, or 36 hr, is obtained. The method has been tried both with and without elimination of the circulation of the hurricane itself. However, it must be pointed out that even in the cases in which the vortex was not eliminated some smoothing was already inherent in the original analysis (the very low central heights of the storm are usually not drawn to) and in the operational JNWP Unit barotropic model.

Tests of this method on four storms yielded 24-hr predictions which have skill about comparable with those of Kasahara. Similar deterioration sets in for periods of 48 hr or more, however. The method proved especially successful up to 36 hr in the case of hurricane Flossy of 1956 as is demonstrated in figure 65. L. Hubert [57] has also made some tests of this method, but using 6-hr time steps, for three of the storms he studied in his initial numerical experiment [56]. The forecasts were an improvement over the original barotropic forecasts in two of the cases, but were worse in the third case. Further operational tests of W. Hubert's method on several storms over the next few years should determine its basic reliability.

DISSIPATION OR TRANSFORMATION

EFFECTS OF UNDERLYING SURFACE ON DISSIPATION

Empirically it has been found that hurricanes generally undergo weakening as they move over land areas or over much cooler ocean waters. Thus, the most obvious dissipative influences are believed to be the increased friction that is encountered as a hurricane moves over land and decreased heat and moisture sources as it moves over either land or cooler waters.

Dissipative Effects of Friction

Friction associated with a hurricane is not negligible even over water since the surface becomes extremely rough as the winds reach very high speeds. However, the energy-producing mechanisms of the storm are usually so great over tropical waters that friction is only a small retarding influence on the hurricane's development. For example, computations by Hughes [61] show that only about 2 percent of the total amount of energy released in a tropical storm is dissipated by surface friction within a radius of 4 deg lat from the storm's center. Of course, friction contributes to low-level inflow, or convergence, and hence actually aids in the concentration and release of heat energy near the center of the storm.

Friction over land is greater than over even rough water so that its dissipative effect is enhanced. The increased angle of inflow (see subsequent section on surface winds) observed in hurricanes over land as compared with over water is clearcut evidence of this increased friction. It has been observed that storms weaken more rapidly over mountainous terrain, such as the Dominican Republic, than over relatively flat country such as the Yucatan or Florida Peninsulas. In fact, over mountainous areas even the most intense hurricanes may lose hurricane intensity after only a few hours. However, the circulation aloft decreases much less rapidly in these cases and hurricane intensity at the surface may be regained within a few hours after moving back over open seas.

Accurate quantitative calculation of the amount of filling to be expected from friction is very difficult in view of the generally poor theoretical knowledge of frictional forces. However, Hubert [55] calculated that a hurricane should fill due to friction somewhat less than twice as fast over land as it would over the ocean. From an analysis of the filling of hurricanes moving over the United States in the period 1900-1949 Hubert also concluded that the average rate of decrease of pressure gradient at the radius of maximum winds for several hours after the storm moves onshore is 10 percent per 3 hr. This would result in a decrease of cyclostrophic wind of about 15 percent in 10 hr. From these calculations and findings then it appears that the frictional effect alone (except possibly over very mountainous terrain) is not large enough to dissipate a vigorous hurricane within even 8 to 10 hr after it moves inland. Decreases in energy supply evidently must be considered in conjunction with friction.

Decreases in Heat and Moisture Sources

The role of sea-surface temperature in influencing the development of the hurricane was mentioned earlier in connection with formation and intensification. For a fully developed storm it is to be expected that movement over cooler waters or over land should tend to result in weakening due to the decrease in heat supply near the storm's center [28]. This lack of a warm ocean surface which can maintain a steady heat supply allows the air to cool due to adiabatic expansion as it spirals in across isobars at the surface toward the storm's center. As Byers has pointed out [12], air with an initial pressure of 1010 mb would cool about 2-3°C if its pressure were reduced to 975 mb near the storm's center. Thus if this cooling is not counteracted by heating from a warm water surface the storm is likely to develop a cold core which would reduce the intensity of the hurricane circulation. Likewise low-level cooling over the entire storm area cuts the vertical instability thereby tending to damp convective activity in the storm. Willett [160] and Gherzi [36] point out that cooling at the surface by only a few degrees makes a very substantial cut in the storm's energy intake.

The rapidity with which the decay of a tropical storm's circulation occurs depends upon the size of the storm as well as the coolness of the underlying surface. Small hurricanes off the coast of Lower California, for example, are usually observed to degenerate rapidly as they move over the cold waters of the eastern Pacific. On the other hand, large hurricanes in the Atlantic usually undergo very slow weakening as they move over cool waters north of about latitude 30°N. The relatively rapid filling of storms over land, which cannot be fully explained on the basis of frictional effects, is apparently abetted by this removal of the surface heat source. Thus storms over land may soon acquire a cold core with a consequent decrease in the slope of the isotherms from the outer to the inner boundaries thereby tending to destroy the circulation. In most cases, after the storm has moved over land, an adequate moisture supply is still available (observed heavy rainfall in many tropical storms over land forcefully bears this out) and heat of condensation is still supplied rather copiously. So, apparently the decreased sensible heat supply from the surface must be the leading energy factor responsible for filling over land.

DISSIPATION DUE TO CIRCULATION INFLUENCES

Dynamical factors favoring hurricane dissipation similarly must be the reverse of those factors favoring hurricane intensification. Forecasters generally look for circulation changes that will decrease convergence in low levels, decrease divergence at high levels, or advect drier, cooler air in low levels. Once a storm is fully developed, however, it is doubtful that even rather radical changes in surrounding sea-level pressure systems could significantly reduce low-level convergence, which is almost self-perpetuating by virtue of the frictional influence and the accelerations of the air spiraling in toward stronger pressure gradients. However, it is quite possible that flow patterns may realign in such a way that drier and cooler air may feed into the storm in low levels. Also, decreasing upward motion in middle levels may be brought about by southward shifting of the westerlies into the Tropics so that the anticyclonic shear side of the westerlies with its typical broad areas of subsidence is brought over the storm. Likewise the replacement of divergent flow patterns at high levels by convergent patterns (e.g., the circulation associated with an upper cyclonic vortex) will usually signify filling for the tropical storm. Most of these ideas are mainly qualitative at present, however. There is definitely some need for better empirical verification of these rough theoretical expectations. It is hoped that future numerical prediction models designed for tropical systems will be capable of predicting weakening of the hurricane as a function of such circulation influences.

TRANSFORMATION TO EXTRATROPICAL CYCLONE

Many hurricanes which move into temperate latitudes transform into or combine with extratropical cyclones. When hurricanes encounter the polar front and the associated trough aloft they frequently begin to intensify in response to the usual middle latitude effects such as advection of cyclonic vorticity aloft and baroclinic instability. In the transformation the storm center becomes located in the band of strong thermal gradient, and the circulation of the storm expands. In most cases in the Atlantic, as pointed out by Sawyer and Ilett [132], the transformed storm becomes a major feature of the circulation. Even though the storm takes on many typical extratropical features, it may still retain for some time such tropical characteristics as intense winds near the center, vestiges of an eye, and heavy rainfall.

Storms which travel mainly over the oceans as they proceed toward middle latitudes are more likely to survive long enough to reach the polar front than those storms which go over extensive land areas. As discussed above the dissipative effects over land are much stronger than over water, even when the water is somewhat cooler than in the region of the storm's formation and development. In fact, over the temperate Atlantic, Sawyer and Ilett [132] have found that most hurricanes undergo little change in intensity for periods of several days prior to their interaction with the polar front.

Many major storms which have affected the east coast of the United States were in the process of transforming into extratropical cyclones as they moved up the coast. Notable among such storms were the two major New England hurricanes of 1938 and 1944 and hurricanes Carol, Edna, and Hazel of 1954. All of these storms maintained or increased their intensities even after they had been moving over colder coastal waters or over land for some time. Details of the transformation of the New England storm of 1938 are given by Pierce [119]. As discussed earlier each of the three major storms of 1954 moved northward along the east coast at a time when a long-wave trough was deepening between the Mississippi Valley and the east coast. These trough intensifications not only affected the motions of these storms, but also provided mechanisms for extratropical cyclone development which served to maintain the storms against the dissipative effects of friction and the weakening oceanic heat and moisture sources. Interesting details of the later stages in the transformation of Hazel are given by Knox [78].

Some tropical cyclones, however, may weaken upon reaching the polar front. This is most likely when the flow aloft over the front is anticyclonic or of a weakening cyclonic type. If the storm is moving slowly, it is especially susceptible to rapid weakening as cold air enters its circulation near the surface. For, as pointed out by Pierce [119], this situation would allow the cold air to sweep rapidly around the storm's center in low levels, thereby occluding the tropical air. Takeuchi [149] refers to many Pacific typhoons which, after reaching the southern extremities of polar fronts at the surface, weaken and decay because they are still too far south of the region of strong westerlies aloft.

STORM EFFECTS

SURFACE WINDS

Introduction

High surface winds are one of the hurricane's most destructive features, because they not only have direct effects in threatening life and property, but also play a major role in the production of storm surges which inundate coastal sections (to be discussed below). The forecasting of high winds for a given locality consists of three essentially quantitative predictions - speed (sustained and gusts), direction, and duration. All of these are of course closely related to the behavior and characteristics of the particular storm. Our knowledge of the wind field surrounding a tropical storm is far from complete since observations of high winds are difficult to make from shipboard, while at land stations anemometers are often blown away when wind speeds exceed about 105 kt [125]. In recent years, however, aircraft reconnaissance* and specially constructed anemometers have been providing much additional information on hurricane wind fields. Nevertheless, it is still usually necessary to rely on the pressure field to estimate and predict considerable portions of the hurricane wind field.

Observed Wind Structure

The generalized distribution of winds relative to the center of tropical storms has been known for many years, but details of the wind structure have only been forthcoming in recent years. A summary by Hughes [61] of data from a large number of U.S. Navy reconnaissance flights over the Pacific has provided an excellent average picture of the wind field near 1000 ft surrounding mature typhoons (at distances more than 0.5 deg lat from the center). The average distribution of total wind speed found in the case of moving storms is shown in figure 66. Note that the maximum winds are found in the right rear quadrant and that in general higher winds are found to the right rather than to the left of the center, which confirms earlier studies by Cline [14]. A similar wind distribution based on surface data has been presented by Myers and Jordan [101] for the New England hurricane of September 1938 as it moved across Long Island into Connecticut. The asymmetry of winds relative to moving storms has often been attributed to the coincidence of the rotary and translatory winds on the right side of the storm and their opposition on the left side. However, there are many cases when the differences between the winds over the right and left sides of the storm are greater than can be explained by the effect of the storm's motion. Sherman [141] reasoned that there is an inherent asymmetry in the flow relative to the moving storm which also contributes to this greater concentration of high winds on the right side of the storm.

Considering the averaging process used in obtaining figure 66 it is remarkable that a maximum greater than 90 kt was obtained. In individual storms maximum winds of about 140 kt have been observed at land stations while over the sea and at higher elevations it has been estimated that speeds of about 175 kt occur [125]. A table of maximum wind speeds observed in hurricanes at United States Weather Bureau coastal stations may be found in [155].

With the aid of a network of weather stations

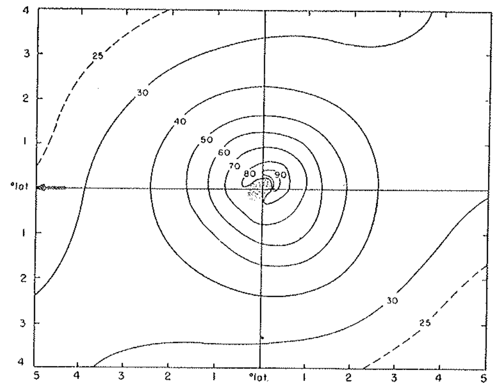


Figure 66. - Total wind speed (in kt) at about 1000 ft relative to tropical storm centered at origin. Speeds are averages for 12 large storms in the Pacific. Arrow indicates direction of storm motion. (After Hughes [61].)

maintained on and around Lake Okeechobee, Fla., the Hydrometeorological Section of the Weather Bureau has studied the detailed structure of wind fields associated with the passage of several hurricanes [63, 99, 134]. In this work wind data were subdivided according to whether they were observed over water, moving from water to land, or moving from land to water. It was found that on the average, other things being equal, off-water wind speeds were 89 percent of over-water winds [155]. Off-land winds were a lower and more variable fraction of over-water winds, depending on the character of the land surface. At Lake Okeechobee the off-land wind averaged between 60 and 74 percent of over-water speeds with the higher percentages occurring with higher wind speeds.

Relationships between observed and gradient winds were also determined for these Lake Okeechobee cases, and were used to estimate surface wind distributions for all the principal hurricanes affecting the United States between 1900 and 1949 [134]. Further reference to these relationships between wind and pressure gradient will be made later, but among the interesting findings concerning the distribution of wind speeds around the hurricane are some average figures for the radius of maximum wind speed (i.e., the distance from the storm center at which the strongest winds occur). These are given for various categories of storms in table 6. Note that the maximum winds tend to be farther from the storm center for areas farther to the north and also for storms with higher central pressure.

The size of the area of high winds is generally of great interest to the forecaster, not only for

*A very recent study by Hawkins [46] of the relationship between hurricane winds at flight levels (700 mb and higher) and low-level wind data indicates that good estimates of winds near the surface can be made through use of reconnaissance data.

Table 6 - Radius of maximum winds (naut mi) in United States hurricanes, 1900-1949 (from table 11 of [99]).

		Texas	Mid-Gulf	Florida Peninsula	Florida Keys	Atlantic (north of Florida)
Storms with central pressure less than 965 mb.	Mean radius	22	28	23	18	38
	Range	12-35	24-31	12-48	6-28	26-49
	Number of storms	9	4	11	8	4
Storms with central pressure between 965 and 982 mb.	Mean radius	27	43	31	19	45
	Range	11-75	18-88	25-43	-	13-89
	Number of storms	7	12	5	1	11

predicting the areal coverage of these winds, but also for estimating their duration at a given locality. According to Dunn [25] the area of high winds varies with a number of factors such as the maturity of the storm, the pressure gradient, and the central pressure. In large storms the area of hurricane winds (i.e., 64 kt or greater) exceeds 100 mi in diameter, while in smaller storms it may be as small as 25-35 mi. Note that in Hughes' average distribution of wind speeds (fig. 66) the area of hurricane speeds is about 140 mi, but his data were averages for mature Pacific typhoons. Gale winds (30 kt or more) associated with hurricanes sometimes cover an area 500-800 mi in diameter or more. It has been stated [25, 115] that the maximum extent of strong winds is usually in the direction of the major subtropical anticyclone, which is usually located to the right of the storm. However, inspection of figure 66 does not reveal any such asymmetry for speeds less than about 70 kt.

Thus far only sustained wind speeds have been discussed. The highest winds, of course, occur in shorter-period gusts (e.g., maximum speed measured over a 2-sec interval). On the average, gust speeds are about 1.5 times as large as the sustained wind at a height of about 30 ft above the ground [155]. Although it is doubtful that there is any large-scale regional variation in the gust factor (i.e., the ratio of gust speed to sustained speed), it is known to decrease with height and with increasing speed and to increase with roughness [99].

The direction of winds around a hurricane is usually expressed in terms of the angular deviation of the wind from a circular path centered in the middle of the storm. Since surface winds mainly flow toward the storm center this is called the angle of inflow, or the angle of in-curvature. The in-curvature field for the cases studied by Hughes [61] is shown in figure 67. Note that the in-curvature is at the maximum to the rear of the storm and at the minimum in front of the storm. At first glance this might imply that the air to the rear of the storm is approaching the storm center at the most rapid rate, but since these storms are moving this is not the case. In fact, if the storm movement is subtracted from the total velocity field, it is found that the air in front of the storm is approaching the center most rapidly (fig. 68). Hughes has stated that his data are unreliable within a radius of about 35 mi from the center of the storm. It has been suggested [155] that the average angle of inflow from the storm center outward to near the radius of maximum wind is about 20° and about 25° outward from about 10 mi beyond the radius of maximum wind. These figures as well as Hughes' are for ocean areas and it is to be expected that the in-curvature angle would be considerably greater over land where friction plays a much greater role. Willett [160] states that Horiguti found average in-curvature angles of 38° over land as compared with 23° over water.

Details of the wind field vary markedly from one storm to the next so that most of the average features which have been mentioned above tend to give an over-simplified picture of the hurricane wind field. Detailed studies of winds in individual storms have revealed some very interesting information about the occurrence of high winds. For example, Mook [90] found that the peak gusts accompanying hurricane Hazel of 1954 occurred

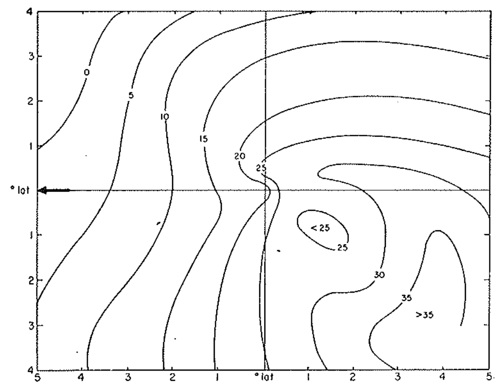


Figure 67. - Field of in-curvature (angle of inflow) of winds (in degrees) relative to tropical storm centered at origin. Arrow indicates direction of storm motion. (After Hughes [61].)

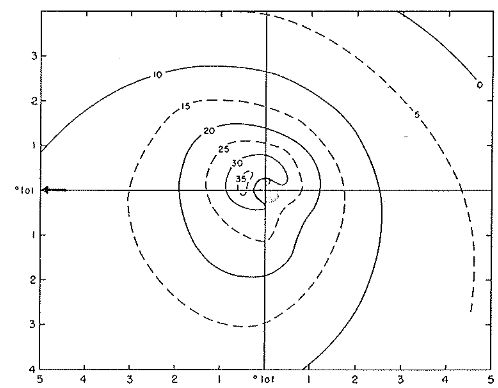


Figure 68. - Radial velocity (in kt) relative to moving tropical storm center. Arrow indicates direction of storm motion. (After Hughes [61].)

with the passage of definite convergence lines in the surface wind field.

In regions of rugged terrain the wind field associated with hurricanes or tropical storms naturally deviates most radically from the average wind structure found over the oceans. Prediction of winds at particular stations in mountain regions must be based on some empirical study of winds associated with various positions and intensities of hurricanes that have affected the station in the past. An example of the type of approach that may be used to handle this problem is the recent study by Fogg and Wang [30]. They have demonstrated how winds at Taipei and Tainan, Formosa respond in varying fashion to typhoons affecting the Formosa area.

Determination of Winds from the Pressure Field

Since wind observations are often quite inadequate around a hurricane it is usually necessary for the forecaster to estimate at least portions of the surface wind distribution from the pressure gradients and curvature of the flow. For prognostic purposes, even if observed winds were available, pressure-wind relationship would have to be used to an even greater extent since virtually all methods of hurricane prediction are designed to handle the pressure distribution and not the wind field. Naturally the many observed features of hurricane wind fields mentioned in the preceding section would also be used to aid in prognostication of the wind distribution associated with the predicted storm, but this knowledge provides only a rough guide as to the winds that may be expected in the storm in question.

It will be recalled that data from Lake Okeechobee were used to establish relationships between observed winds and gradient or cyclostrophic winds in hurricanes [99] so that more complete information about the average wind fields of past storms could be obtained. These relationships can be applied to the current or predicted hurricane as well. It was found in this work that the over-water wind at anemometer level varies between about 60 and 85 percent of the gradient wind depending upon the distance from the center of the storm, which is expressed relative to the radius of maximum winds (R) (fig. 69). If surface winds over land are desired, these values can be reduced further by applying the percentages cited in the preceding section - winds coming onshore are about 89 percent of the over-water winds, winds over land areas (designated as "off-land") average about 60 to 74 percent of the over-water winds.

Unfortunately gradient wind measurements are subject to considerable error in the high wind zones of hurricanes since the very close isobaric spacings can hardly be drawn with sufficient accuracy on a prognostic chart, or even on an observed chart. However, the pressure field in a hurricane may be used in a less refined way to obtain some estimate of the winds. For example, Fletcher [29] gives a formula for computing the maximum wind in a hurricane as a function of the storm's central and peripheral pressures. This formula, which is derived from the cyclostrophic wind equation by making several other assumptions about the storm's pressure and wind structure, is

$$v_m = K_m\sqrt{p_n - p_o} \,, \tag{5}$$

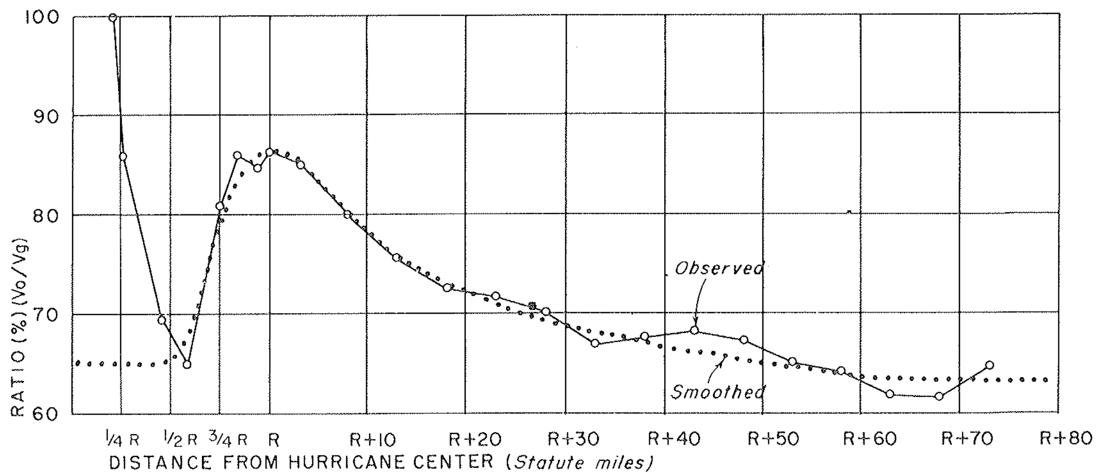


Figure 69. - Variation with distance from hurricane center of ratio of observed over-water winds (10-min averages) to gradient winds. Distance scale is relative to radius of maximum winds. Solid line is observed for a hurricane in 1949, dotted line is smoothed version of solid line except close to hurricane center where observed high values are apparently spurious. (After Myers [99].)

where v_m is the maximum wind, K_m is an empirically determined constant, p_n is the sea level pressure at the outer edge of the storm circulation, and p_o is the sea level pressure at the storm's center. Myers [100] has recently presented some values for K_m calculated from observed wind and pressure in a few storms for various categories of friction and duration of the wind. A summary of the more representative values of K_m are given in table 7. Equation (5) can thus be applied by the forecaster to calculate the maximum wind in an observed or prognostic hurricane, providing he can obtain a good estimate of the central pressure. The constant K_m has been derived in units such that with the pressure difference in mb, v_m is in kt.

Close attention to the pressure field is especially important in predicting the surface wind field when there are fairly rapid changes in the intensities and/or relative positions of the hurricane and the surrounding pressure systems. The case of rapid filling of a hurricane which frequently occurs as it moves over land is very well known, of course; winds diminish rapidly in association with

Table 7 - Values of K_m of equation (5) calculated from observed maximum surface winds and pressure differences for various wind categories in several hurricanes. (From [100].)

Wind Category Frictional	Duration	Date	Location	K_m (kt/mb $^{\frac{1}{2}}$)
Off-land (or over-land)	10-min av.	Aug. 26-27, 1949	Lake Okeechobee, Fla.	7.0
	1-min av.	Aug. 31, 1954	Brookhaven, N. Y.	6.6
Off-water	10-min av.	Aug. 26-27, 1949	Lake Okeechobee, Fla.	8.8
	10-min av.	Sept. 21, 1938	South shore of Long Island	9.0
	10-min av.	Sept. 14, 1944	Rhode Island coast	8.9
Over-water	10-min av.	Aug. 26-27, 1949	Lake Okeechobee, Fla.	9.2
Off-land	Gusts	Aug. 26-27, 1949	Lake Okeechobee, Fla.	11.8
	2-sec av.	Aug. 31, 1954	Brookhaven, N. Y.	10.9
Off-water	Gusts	Aug. 26-27, 1949	Lake Okeechobee, Fla.	12.7

weakening pressure gradients. Another important case, which has generally been given insufficient attention, is the approach of a hurricane and an adjacent anticyclone. For example, a storm may be moving northward along the South or Middle Atlantic coast of the United States while an anticyclone remains stationary over New England. The increased pressure gradients that develop between the two systems result in a rapid spread of high wind speeds northward along the coast for several hundred miles from the hurricane center. In such situations gradient or geostrophic wind estimates from accurate prognostic charts can be of material assistance in predicting the development of gale- or hurricane-force winds far from the center of the tropical cyclone.

RAINFALL

Introduction

Although rainfall is one of the hurricane's fundamental attributes, the prediction of the location and intensity of rainfall for periods of about 12 to 24 hr in a given storm is a difficult task, even when average amounts over areas of 50 to 100 mi in diameter are considered. In current practice the forecaster depends considerably on past situations (analogue or climatological approach), or on extrapolation of current observations of precipitation associated with the storm in question. The latter method is most useful for periods up to a few hours and it has been aided particularly in recent years by the use of radar [129]. Considerations of the dynamical and thermodynamical processes associated with hurricane rainfall are used mainly in a subjective fashion at present since more objective methods are still largely in the developmental stages. However, some promising efforts along objective, physical lines are now being made.

One important observational problem which adds to the difficulties of rainfall prediction in hurricanes is the great inaccuracy of measuring precipitation in very high winds. This has been emphasized by Riehl [125] and also by Dunn [25], who states that the loss of rain from gages may reach 50 percent in hurricane winds. This problem will probably be solved as more is learned about the relationships between brightness of radar echoes and intensity of rainfall [6, 51].

Distribution of Rainfall Relative to the Tropical Storm

Observations have shown that the distribution and intensity of rainfall around a tropical cyclone may vary markedly from one storm to another. However, storms at various stages of development and in various locations do have some characteristics in common.

Rainfall is distributed fairly symmetrically with respect to the storm's center when the storm is in its immature or developing stage or when it is moving very slowly. The most intense precipitation is usually located not far outside the wall of clouds surrounding the eye of the storm. This may be anywhere from about 10 to 80 mi from the center of the storm. Actually, since many of the storms in this category are located over the oceans, it has been difficult to get quantitative verification of this symmetrical rainfall distribution. However, there have been observations confirming this type of distribution for storms passing over Puerto Rico [25] and for stationary storms along the coast of the Gulf of Mexico [14]. Radar has recently shown in the case of hurricane Ione of 1955 [129] how the main rain shield tends to become circular around the eye of the hurricane when the storm becomes quasi-stationary. Indirect evidence for this type of rainfall distribution in several large Pacific typhoons has been presented by Hughes [61] who deduced such a pattern from his computed fields of convergence of the low-level winds. His data point to the likelihood of a somewhat greater concentration of precipitation to the rear of the storm center with respect to its direction of motion.

Hurricanes which are in their mature stage and/or beyond their point of recurvature (cf., [25, 160]) generally develop an asymmetrical precipitation distribution with more rainfall occurring on the forward side of the storm and considerably less to its rear. Much of this asymmetry is probably associated with the relatively rapid motion of hurricanes in these stages of their development since maximum low-level convergence would tend to be associated with the large pressure falls ahead of the storm and low-level divergence would accompany the rising pressures to its rear. Empirical evidence for the location of the maximum precipitation in advance of the hurricane has been presented by Cline [14] for storms entering the United States along the Gulf of Mexico, by Deppermann [22] for storms in the Philippines, by Bond and Rainbird [8] for storms in the region of Australia, and by Rockney [129] from radar observations of storms moving near or approaching the Atlantic coast of the United States in the vicinity of the Carolinas. Figure 70, which is a schematic picture of the typical appearance of four major east coast hurricanes on radar, illustrates the great concentration of the more solid bands of precipitation in the forward semi-circle of the advancing storm and the general lack of precipitation to the rear (especially the left rear). It has been argued

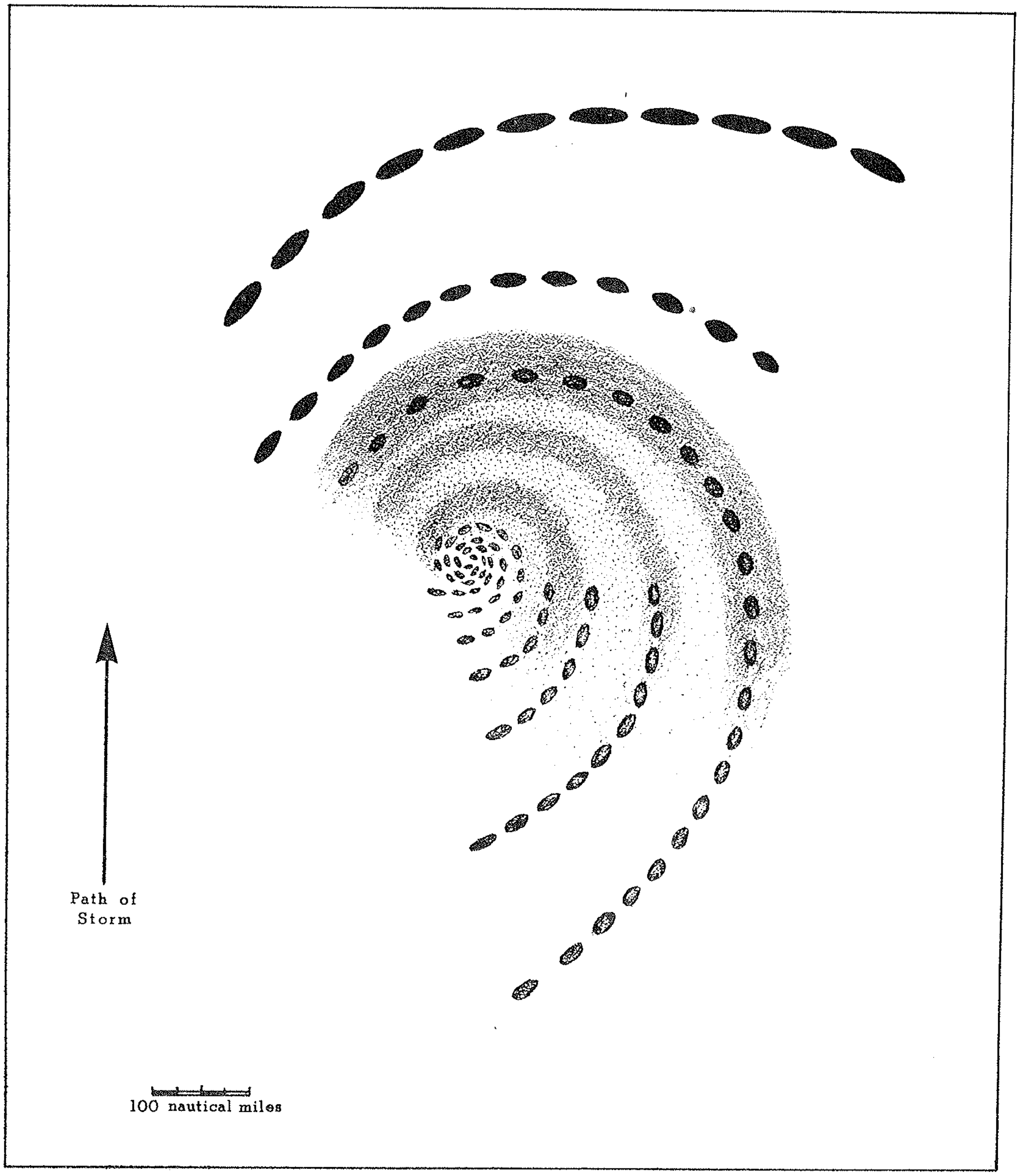


Figure 70. - Schematic illustration of the typical appearance of four major east coast hurricanes on radar showing typical banded and cellular structure of rain areas concentrated mainly in forward semicircle of the advancing storm. General lack of precipitation is found to the left rear of the storm.

[61, 120, 125] that these findings about the bulk of the precipitation being located in advance of the storm are due to the particular locations of these observed storms with respect to coastal areas. These arguments have some validity, but evidence from small islands relatively free of orographic effects, from synoptic ship and reconnaissance observations, and from radar generally points to the prevalence of this precipitation pattern over the oceans too during the stage of the storm we are considering here.

Differences in precipitation between the two forward quadrants of the hurricane have been noted in particular areas. Cline's [14] study localized the maximum precipitation to the right forward quadrant with maximum intensity of rainfall located some 60-80 mi from the cyclone center. He attributed this concentration to a zone or line of convergence between the surface winds of the right rear quadrant and those of the right front quadrant. Actually the observed maximum precipitation was found some 50-100 mi in advance of this convergence line. Storms moving northward along the east coastal sections of the northeastern United States have frequently exhibited their maximum rainfall in their left front quadrants. This has been attributed [74, 160] to the increased ascent of moist air caused by the frequent presence of fronts in the left front quadrant of such storms, the increased convergence due to friction near the coastline, and the sharply ascending topography located not far inland from the coastal plain. Somewhat drier air coming offshore in many cases will also serve to cut off precipitation to the rear of these storms very abruptly. These coastal effects are apparently so great that many mature storms with relatively rapid motion have their maximum precipitation in the right rear quadrant if they are traveling with the coastline to the right of their path. This apparently occurs frequently along the south China coast [48, 120] where the very moist tropical air flows onshore after the storm's passage to the west. This same effect probably operated in the famous case of the "Yankee" hurricane of 1935 which moved southwestward along the Atlantic coast from the Carolinas to Florida [151] and yielded (according to Dunn [25]) .04 inches of rain at Miami before its arrival and 3.40 inches afterward.

Detailed studies of some individual storms have suggested that a bimodal distribution of precipitation may exist in many situations, with maximum amounts and duration of precipitation to the right and left of the storm and a relative minimum near the storm path itself. This has been emphasized by Bergeron [5] in his analysis of the major Florida hurricane of September 1947 and also in his reanalysis of precipitation associated with a hurricane studied by Brooks [11].

Some of the heaviest amounts of rainfall in periods of about 12 to 48 hr over sizeable areas have occurred in connection with hurricanes and other tropical cyclones. Frequently the heaviest amounts are observed when a storm stalls and/or orographic influences are pronounced. Since these two factors frequently occur after a storm has moved inland and starts to fill, decaying storms can often produce more rainfall in a given area than the more intense storms which are usually moving more rapidly.

The first comprehensive collection of observed rainfall distributions in the United States associated with tropical cyclones during the years 1900-1955 was recently prepared by Schoner and Molansky [137]. This publication shows isohyetal analyses of total storm rainfall as well as amounts for 12, 18 or 24 hr within the period of the storm's influence. Although this collection as it stands will serve as a useful catalogue in which the rainfall of analogous storms may be readily located, climatological summaries of the data are also desirable. One such study of the rainfall climatology of these tropical storms has been made by Schoner [135], who presents data on the frequency and distribution of areal average precipitation for the 24-hr period following passage of tropical storms across various portions of the Gulf and Atlantic coasts of the United States. The data have been averaged over relatively large areas, 100 by 100 mi square, arranged in a grid oriented according to the direction of the storm's path while crossing the coast. As examples of the type of rainfall information provided by this study, average precipitation amounts and frequencies for storms entering the Texas coast are shown in figures 71 and 72. The data were also subdivided according to central pressure and direction of motion of the storms, but differences between various subgroups were relatively minor. Schoner [136] has also obtained generalized isohyetal patterns for periods preceding, during, and following passage of hurricanes across various zones of the Gulf and Atlantic coasts.

Physical Prediction Methods

The basic approaches to the prediction of precipitation are summarized very well by Thompson [152]. Suffice it to say here that the primary parameters which must be considered in efforts at making quantitative, or even good qualitative, precipitation forecasts are moisture, stability, and vertical motion. Most efforts at rainfall prediction, either physical or empirical, have made

MILES

MILES	300–200	200–100	100–0	0–100	100–200	200–300	300–400
600–500	0	0	0	0	0	0	0
500–400	0	0	0	0	0	0	0
400–300	0	0.1	0.2	0.2	0.3	0.1	0
300–200	0	0.2	0.7	1.0	0.7	0.3	0.1
200–100	0	0.5	1.5	1.8	1.2	0.5	0.2
100–0	0	0.5	2.1	2.9	1.4	0.5	0.1
0–100	0	0.2	0.9	1.0	0.8	0.4	0
100–200	0	0	0	0	0.2	0.2	0

Figure 71. - Mean areal average precipitation amounts (in inches) for 35 tropical storms entering the Texas coast. All values are located relative to the position of storm as it crossed the coast and its motion (in direction of arrow) during the 24 hours following coastal crossing. (After Schoner [135].)

MILES

MILES	300–200	200–100	100–0	0–100	100–200	200–300	300–400
600–500	0	03	03	0	0	0	0
500–400	0	03	03	03	03	0	0
400–300	0	11	23	23	29	11	0
300–200	03	20	66	66	63	34	11
200–100	03	46	94	97	86	46	20
100–0	03	43	100	100	97	49	09
0–100	0	20	77	80	60	43	03
100–200	0	0	0	03	18	18	0

Figure 72. - Percentage frequencies of areal 24-hr precipitation occurrence for 35 tropical storms entering the Texas coast. All percentages are located relative to the position of storm as it crossed the coast and its motion (in direction of arrow) during the 24 hours following coastal crossing. (After Schoner [135].)

use of these variables or some indirect estimates thereof. Some of the approaches which offer promise of predicting rainfall associated with tropical storms will be discussed briefly here.

The most important advances in hurricane rainfall prediction are likely to come from the development of numerical methods which will employ dynamically predicted three-dimensional motion and moisture fields to calculate precipitation amounts over relatively small areas of the earth's surface. The first direct numerical predictions of precipitation along these lines were made by Smagorinsky and Collins [145] who achieved relatively good results both quantitatively and qualitatively for 12-hr forecasts in two cases of extratropical storm precipitation using a three-level baroclinic model. However, further applications of virtually the same model to other cases, including rainfall associated with hurricane Diane of August 1955, produced forecasts which were good qualitatively, but which generally failed to call for large enough amounts of precipitation even when considering average amounts over relatively large areas (i.e., about 90,000 km^2). Revisions of this model to include the previously neglected effects of heat of condensation and variations in static stability have resulted in computed vertical motions which are an order of magnitude larger in rain areas than those previously computed [144]. Hence, predicted amounts of precipitation should be brought more in line with observed values even though the model still does not take into account the effects of convective instability. More precise results are anticipated from further experiments with this moist-adiabatic, baroclinic prediction model which are being conducted. Extension of the time period of these precipitation forecasts to as much as about 24 or 36 hr and specification of precipitation over smaller areas will probably be difficult, even in middle latitudes, until more improvements are made in the basic circulation predictions. This problem is more acute in the case of tropical storms since numerical forecasting of the needed details of the storm's circulation for periods of only 12 hr is not feasible as yet. The numerical prediction of even the motion of the storm is in an early developmental stage at the present time as mentioned above.

Thus, from the point of view of current forecasting practice there is at least a temporary need for more simplified physical and empirical approaches to the hurricane rainfall problem. Unfortunately most of the relationships found in the past have been of the concurrent type which are not useful for more than a few hours from the latest observations unless prognosis of the hurricane's circulation attains considerably more skill than it has now. Nevertheless these relationships have at least been useful in that they provide the forecaster with some better knowledge on which to

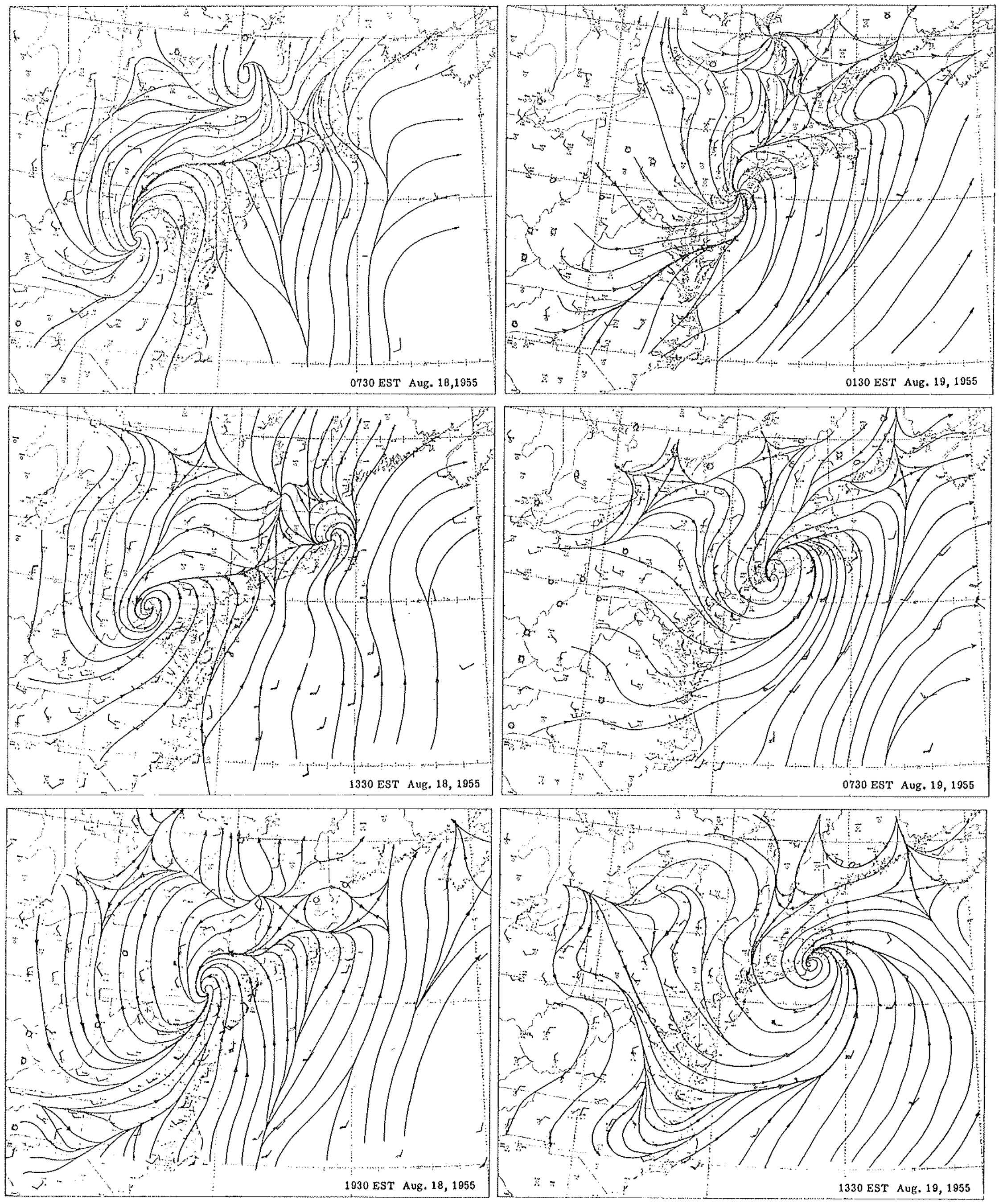


Figure 73. - Surface streamlines at 6-hr intervals, August 18-19, 1955 illustrating strong convergence lines and pronounced cyclonic indrafts associated with areas of very heavy precipitation in northeastern Pennsylvania and southwestern New England (hurricane Diane). (After Mook [91].)

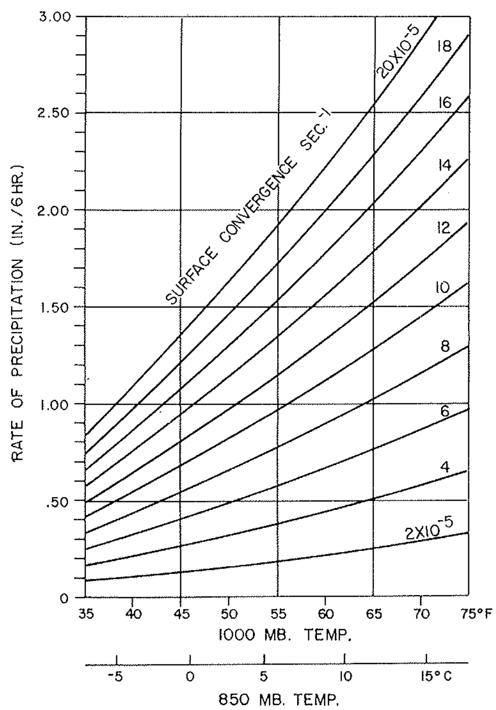


Figure 74. - Rates of precipitation from pseudoadiabatically ascending air for various 1000-mb (or 850-mb) temperatures and values of surface convergence, assuming a linear decrease of convergence with height to a value of zero at 4.5 km. (After Peterson [117].)

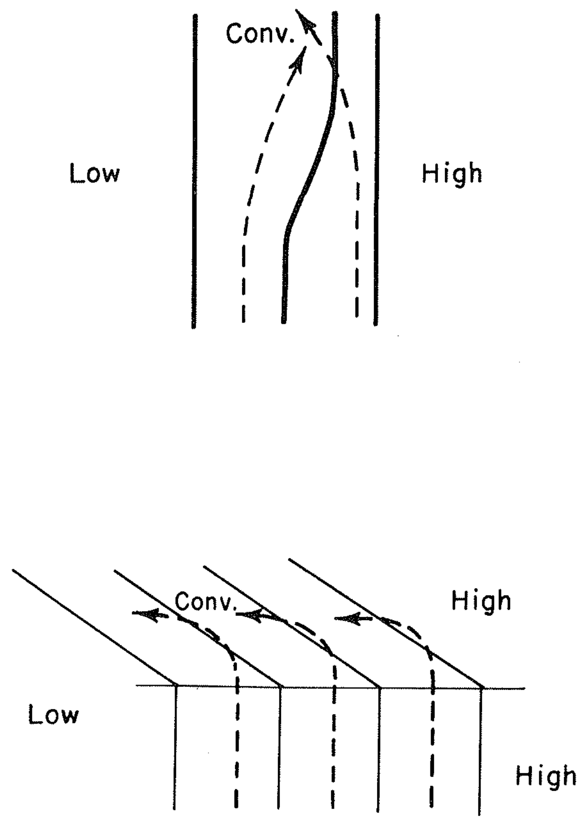


Figure 75. - Two examples of surface isobaric configurations associated with horizontal convergence in lower levels. Solid lines are isobars, dashed lines are trajectories of air. (After Gilman et al [37].)

base the subjective estimates of rainfall which he is required to make.

The connection between low-level convergence of the winds and rainfall was recognized by Cline [14] who, as mentioned earlier, found that precipitation was concentrated ahead of convergence lines in the surface winds. This was recently illustrated by Mook [91] who found that pronounced convergence lines in the surface flow were closely associated with the flood-producing rains of hurricane Diane of 1955 (fig. 73). Also of importance in augmenting the general vertical motion field which developed in advance of this storm was the forced ascent of the air over the topographic barriers in southwestern New England and northeastern Pennsylvania [91, 92]. The importance of orography has been stressed in other cases of very heavy rainfall associated with tropical storms (e.g., 82]). A nomogram for estimating the rate of precipitation from observed values of low-level convergence and moisture, making certain assumptions regarding the distribution of moisture and convergence with altitude, has been constructed by Peterson [117] and is shown in figure 74.

A method has recently been devised by Gilman et al [37] to predict areas of convergence and compute precipitation amounts for periods up to about 24 hr in advance. The method is based on the recognition that air parcels passing through certain types of stationary or changing isobaric configurations will undergo convergence. For example, a zone of pronounced cyclonic isobaric curvature or shear on the surface chart will result in convergence of air parcels near or downstream from that zone (fig. 75). Expected (non-geostrophic) trajectories are constructed for parcels passing through such zones and the associated transport of moisture into the area is calculated. Assuming that a certain percentage of the moisture transported into the designated convergence area will be precipitated, the amount of expected precipitation can be readily computed. The procedure is based on a 12-hr prognostic surface chart so that precipitation amounts can be calculated for periods up to about 24 hr from the latest map. This technique is currently being subjected to routine testing on extratropical systems and is reported to be showing some good results. A special application of this procedure to very short-range rainfall prediction in six hurricane cases has been made by Peterson and Molansky [118]. Rainfall amounts were obtained for a 6-hr period beginning $1\frac{1}{2}$ hr after the time of the latest surface map (prognostic sea level charts were not used in these cases). Their calculated precipitation areas and amounts demonstrate some skill in predicting hurricane rainfall for this short, but often critical, time interval.

If convergence can be measured at several levels in the atmosphere the complete distribution of vertical motion can be obtained and the rate of precipitation can be computed from Fulks' formula [33, 152]. This was accomplished for hurricane Diane of 1955 in the vicinity of Boston by Mook [92] and reasonable rates of precipitation were found. However, this is a contemporaneous relationship which in practice could scarcely be computed before several hours after observation time had elapsed. This approach is essentially what is being attempted by machine except that numerical methods have not been developed to handle convergence of the observed winds as yet. The advantage of numerical approaches, however, is that they deal with vertical motions computed from predicted isobaric height patterns and, hence, offer the possibility of making good precipitation estimates 24 hr or more ahead.

Other methods of predicting heavy rainfall have centered around considerations of patterns of warm-air advection in low levels of the atmosphere, transport of moisture, and areas of instability [1, 87, 146, 148]. These techniques generally have not been tested in hurricane situations, so there is virtually no information presently on their merits as tools for predicting hurricane rainfall. However, pronounced low-level warm advection has been observed in some cases of very heavy rainfall associated with weakening or transforming tropical storms over land (e.g., [82]).

FLOODS

Heavy rainfall associated with tropical cyclones presents an immediate flood threat to smaller streams and the upper reaches of major rivers where rapid rises in stream levels can occur. Serious flooding of downstream portions of large rivers can also result from hurricane rainfall, but usually there is sufficient lag between rainfall and flood stages in these cases that warnings of expected flooding can be issued well in advance. For these situations the river forecasting methods developed for various stations in the major river basins in the United States can be used [81].

Flash flooding, then, is essentially the major flood forecasting problem associated with intense hurricane rainfall. Obviously flash flooding depends primarily on the distribution of rainfall amounts relative to the particular stream or other potential drainage channel which might reach flood stage. So, of course, substantial improvements in flash flood forecasting must depend on improvements in rainfall prediction. However, very-short-period rainfall forecasts or even instantaneous information on current rainfall rates can be of great value in at least providing short-notice emergency warnings on imminent flooding, since there may be up to a few hours lag between the occurrence of heavy precipitation and flooding in all but the smallest streams.

One of the most critical factors in prediction of flash flooding is the initial state of stream levels and water stored in the ground. Considerable rainfall within several days prior to the occurrence of hurricane precipitation will result in nearly immediate runoff of a large percentage of the total precipitation. Some good examples of the effects of differing initial water storage in the ground have been cited in connection with hurricanes Connie and Diane in August 1955 [154]. These figures on rainfall and runoff for several river basins for both storms have been assembled in table 8. The large increases in runoff for Diane as compared with Connie in these river basins are quite remarkable. Connie's precipitation came after a long dry spell in these areas so that much of the water was absorbed by the soil until it became saturated. Meanwhile the runoff from Connie's rainfall raised the very low levels of stream channels and reservoirs. Thus, when Diane's heavy rains came along in the same areas within a week, much of the water was forced to run off so that streams and reservoirs, which already had adequate water levels, were soon overflowing. In addition, the fact that Diane's rains were heavier than Connie's in many areas contributed further to increased runoff with Diane. These high rates of runoff resulted in flood stages being reached in many localities within a few hours after the heaviest rains started and in flood crests occurring only a few hours after the heaviest rains were over.

Fortunately the river or flood forecaster can at least estimate the degree of saturation of the ground prior to the hurricane rainfall from his knowledge of rainfall of the recent past. In addition he may have at hand current observations of stream and reservoir levels. With such information available the effect of predicted heavy precipita-

Table 8 - Average precipitation and runoff in selected river basins during hurricanes Connie and Diane of August, 1955.

Basin	HURRICANE CONNIE Total average precipitation (in)	HURRICANE CONNIE Runoff (in)	HURRICANE CONNIE Percentage runoff	HURRICANE DIANE Total average precipitation (in)	HURRICANE DIANE Runoff (in)	HURRICANE DIANE Percentage runoff
Rappahannock River above Fredericksburg, Va.	5.0	0.9	18	5.3	3.0	57
Lehigh River above Bethlehem, Pa.	5.3	0.9	17	8.0	3.2	40
Farmington River above Rainbow, Conn.	7.3	0.8	11	14.6	9.3	63
Naugatuck River above Thomaston, Conn.	8.7	1.4	16	14.1	10.2	72

tion amounts occurring with the passage of a tropical storm can be better estimated, and preliminary alerts may be issued on flooding probabilities. As storm precipitation begins to occur in heavy amounts over the area of interest, speedy collection and analysis of precipitation observations plus intimate knowledge of the expected behavior of the storm and its precipitation pattern in the immediate future, should allow for issuance of detailed bulletins on flooding expected in the next few hours at specific locations along the streams in the area. This type of flood forecasting requires very close liaison between the hurricane forecaster and the river or flood forecaster, plus an excellent observational network with good communications. An outstanding example of the issuance of preliminary alerts and then shorter-range emergency bulletins in a hurricane flood situation has been described by Higgs [49], who credited good predictions of flood conditions to timely reports from an alert observer. Until forecasting of flash floods can be put on a more objective basis, close attention to the latest observations, good subjective evaluation of the situation, and alert teamwork will enable forecasters to issue useful short-period hurricane flood predictions in most cases.

STORM TIDES

Introduction

As a hurricane moves close to or across coastlines it is accompanied by an increase in the tide level above the normal value for the given time and place. For weak hurricanes or tropical storms this increase may be no more than 4 ft. For the more intense hurricanes the tides may rise more than 15 ft above normal.

The effects of storms and normal tides on sea level are almost independent along the open coast. Thus it is convenient to consider these two effects separately. The storm surge is defined as the difference between the actual tide as influenced by a meteorological disturbance (i.e., storm tide) and the tide which would have occurred in the absence of the short-period meteorological disturbance (i.e., normal tide).

The practical importance of a given storm surge will depend on the stage of the normal tide at the time of the storm tide. An illustration of this is given in figure 76, where the peak storm surge of 4.2 ft, occurred at about 2200 EST, near the time of normal low water; but the peak storm tide occurred at about 1500 EST, near the time of normal high tide, with a surge of only 2.3 ft. Also of importance is the elevation of the land in the region of the storm. Waves and swell, with periods of only a few seconds, also add greatly to the damages caused by flooding in regions that are inundated by storm tides. The effects of these short-period waves also interfere with the collection of data on the actual tide elevations during a storm and considerably handicap all studies of actual storm tides. Thus it is necessary to con-

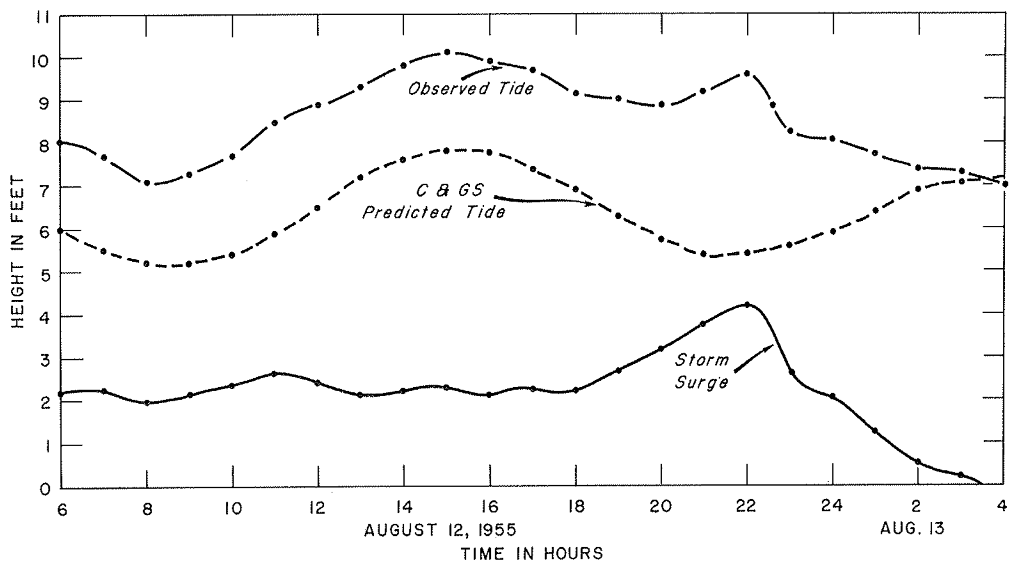


Figure 76. - Observed and predicted (normal) tides and storm surge at Little Creek, Norfolk, Va., associated with hurricane Connie, August 1955.

sider the normal tides, the elevation of the land near the coast, and the short-period waves in any discussion of the practical importance of storm surges.

Storm Surge Data Problems

The best storm surge records are obtained from a continuously recording tide gage at a site for which the observations have previously been analyzed for astronomical (or normal) tide predictions, for it is only in this case that the storm surge can be accurately determined. Unfortunately, there are many large gaps in the tide gage network and the peak storm tide can often be determined only by an inspection of the coast soon after the passage of a severe storm. High water marks may be located inside buildings flooded by the storm, and sometimes in natural or artificial basins whose connections with the sea are good enough to permit the passage of the tide, but too tortuous to permit the passage of the high waves prevalent on the outer coast.

Since the elevation of the land and the type of exposure of the place in question play a major role in determining the hazards to life and property which may arise from a given storm surge, it is important that the surge forecaster have on hand precise information concerning land elevations in his area. The most extensive collection of land elevation data available in the United States is that given in the quadrangle maps published by the United States Geological Survey. Elevations are based on a reference of mean sea level - the figures currently being used most widely are from the "Sea Level Datum of 1929." Unfortunately, some elevation data are based on other datum planes and also there is the problem of variation in mean sea level from month to month and year to year. This variation is of the order of one foot and is insignificant for most purposes. However, it may become critical in some communities in the coastal lowlands. Further discussion of the mean sea level problem may be found in Appendix III of [42].

The Normal Tide

The normal tide is a quasi-periodic rise and fall of the level of the sea, having periods of approximately 12.5 and 25 hr. Predictions of high and low water for each day of the year for 28 locations along the Atlantic and Gulf Coasts of the United States are contained in the publication, Tide Tables, East Coast North and South America. These published tide predictions may be regarded as the sum of two components. The largest component in most coastal areas is the semidiurnal variation of water level from its mean value for the tidal period. This is due almost entirely to gravitational effects and can be predicted with a high degree of accuracy at most locations. The second component, the mean sea level for the tidal period, is mainly due to such meteorological and oceanographic effects as prevailing winds, pressure gradients, temperature of both air and water, and variation in salinity of the water. The normal seasonal variation in sea level, as computed from an analysis of many years of record, is included in the tide predictions. It is well known that actual seasonal variations in any given year in wind and pressure rarely conform to the normal. Consequently, the mean sea level for a month may be more than a foot above or below the predicted value based on the normal or average seasonal cycle. Departures of 2 or 3 ft may persist for several days.

There is also a gradual trend toward rising sea level along the Atlantic and Gulf Coasts of the United States which is not taken into account in the predictions. As a result, observed sea levels are generally higher than predicted values. From the standpoint of coastal flood damage, this trend toward rising sea level presents an added source of danger and makes the seasonal variations in sea level even more important. When these two effects, anomalies in the general circulation of ocean and atmosphere and a trend toward rising sea levels, are considered, the mean level of the sea may be as much as 1.5 ft above the mean sea level shown on topographic charts for a month or two at a time. This can be very important in regions with considerable industrial and residential developments at elevations only a few feet above the mean high spring tide level.

The Storm Surge

The high winds and low pressures associated with hurricanes usually lead to significant anomalies in the tide. A gradual rise in the tide level often begins more than 24 hr before the storm makes its nearest approach to a station, but occasionally the tide falls below normal for many hours during the approach of the storm. A rapid rise generally begins about the time gale winds associated with the hurricane are first experienced. The peak storm surge usually occurs within an hour or two after the storm makes its nearest approach to the station. In areas with good drainage conditions, the fall in the tide level tends to be more rapid than the rise, and the tide often drops below normal for a few hours after the storm passes. In marshlands and other areas with poor drainage, many days may be required for the water levels to return to normal. The first storm surge peak is sometimes followed by a series of resurgences. The second storm surge peak, occurring several hours after the storm has passed, may be as high as the first. If the first storm peak occurs near the time of normal low water, and the second coincides approximately with normal high water, this second peak can be the more important [98, 121]. Fortunately, resurgences are not prominent in the region of hurricane landfall, but appear to be important for storms moving approximately parallel to the coast. The storm surge moves through long bays, such as Long Island Sound, as a progressive wave. Consequently, the peak surge at the head of the bay may occur many hours after the peak storm conditions [40]. The storm surge as a function of time at the tide station nearest the point of landfall is shown for four hurricanes in figure 77.

Analogues showing the effects of past storms are essential to an understanding of the hurricane surge. Cline [13, 14] gave a record of the observed tide at one or more stations and the highest observed tide or storm surge at a number of points for many Gulf of Mexico hurricanes. Redfield and Miller [121] have presented similar data for several Atlantic Coast storms. Hubert and Clark [59] treated the peak storm tides or peak storm surges associated with 16 Atlantic and Gulf hurricanes, including most of the data previously published by Cline. Zetler [164] recently presented an exhaustive tabulation of the peak storm surge recorded by the Coast and Geodetic Survey tide gage in Charleston, S.C., during a great many hurricanes. Harris [40] has given the time history of the surge at all Coast and Geodetic Survey tide stations affected by 8 hurricanes. Additional data on past storms are being collected by the United States Army Corps of Engineers and many coastal Weather Bureau offices as well as the Central Office of the Weather Bureau. It is hoped that a more exhaustive collection of the records of the tides during past hurricanes can be published within the next few years.

The data contained in the above reports indicate that maximum storm surge heights usually occur somewhat to the right of the storm center and the region of above normal tides generally extends farther to the right of the storm center than to the left. Deviations from this pattern are occasionally produced by local topography. Storm surge profiles along the open coast for four hurricanes studied by Harris [41] are illustrated in figure 78.

Hydrodynamic Theory of Storm Surges

The complete equations of motion governing storm surge generation have never been solved in

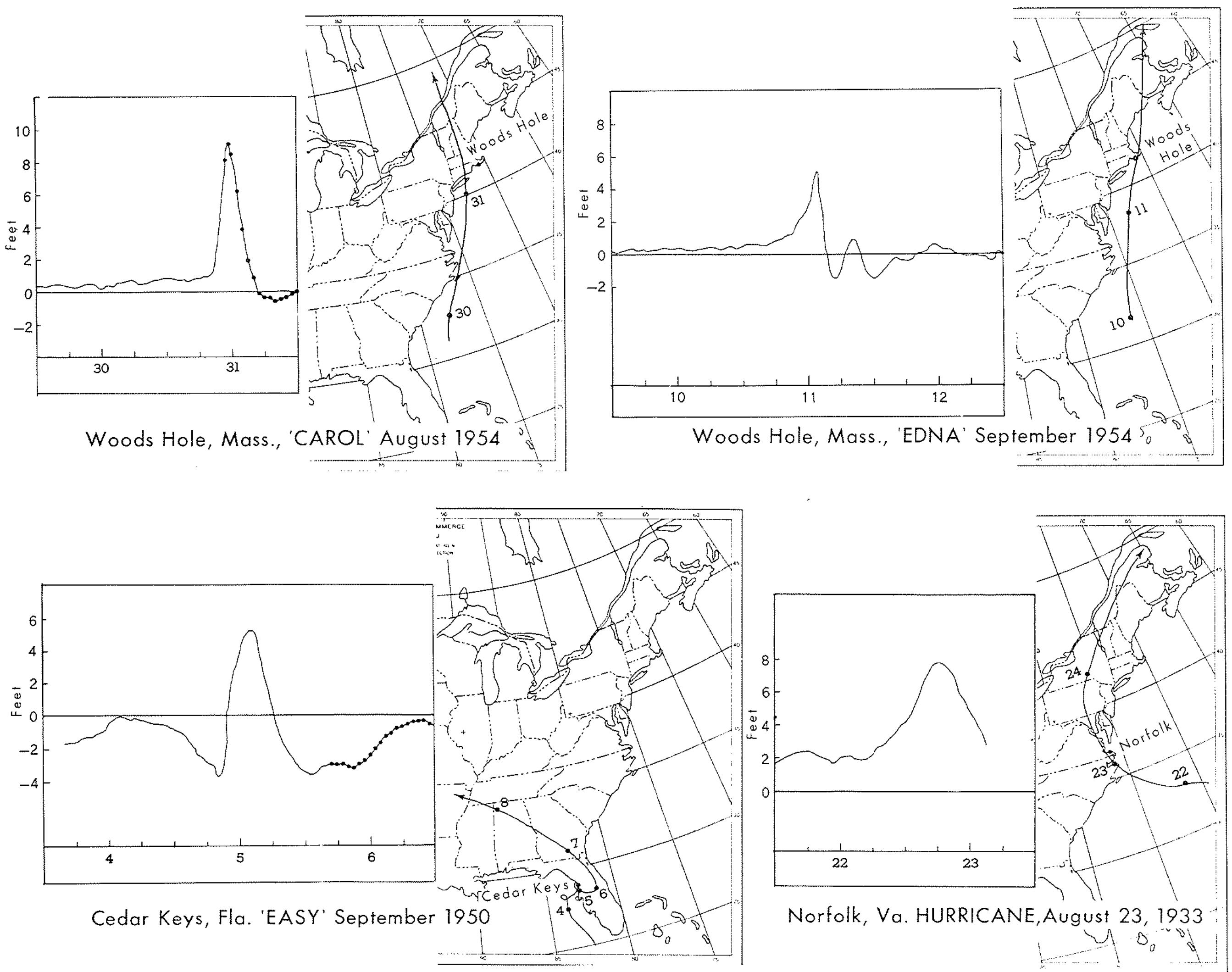


Figure 77. - Examples of storm surges as functions of time in the region of hurricane landfall. (After Harris [41].)

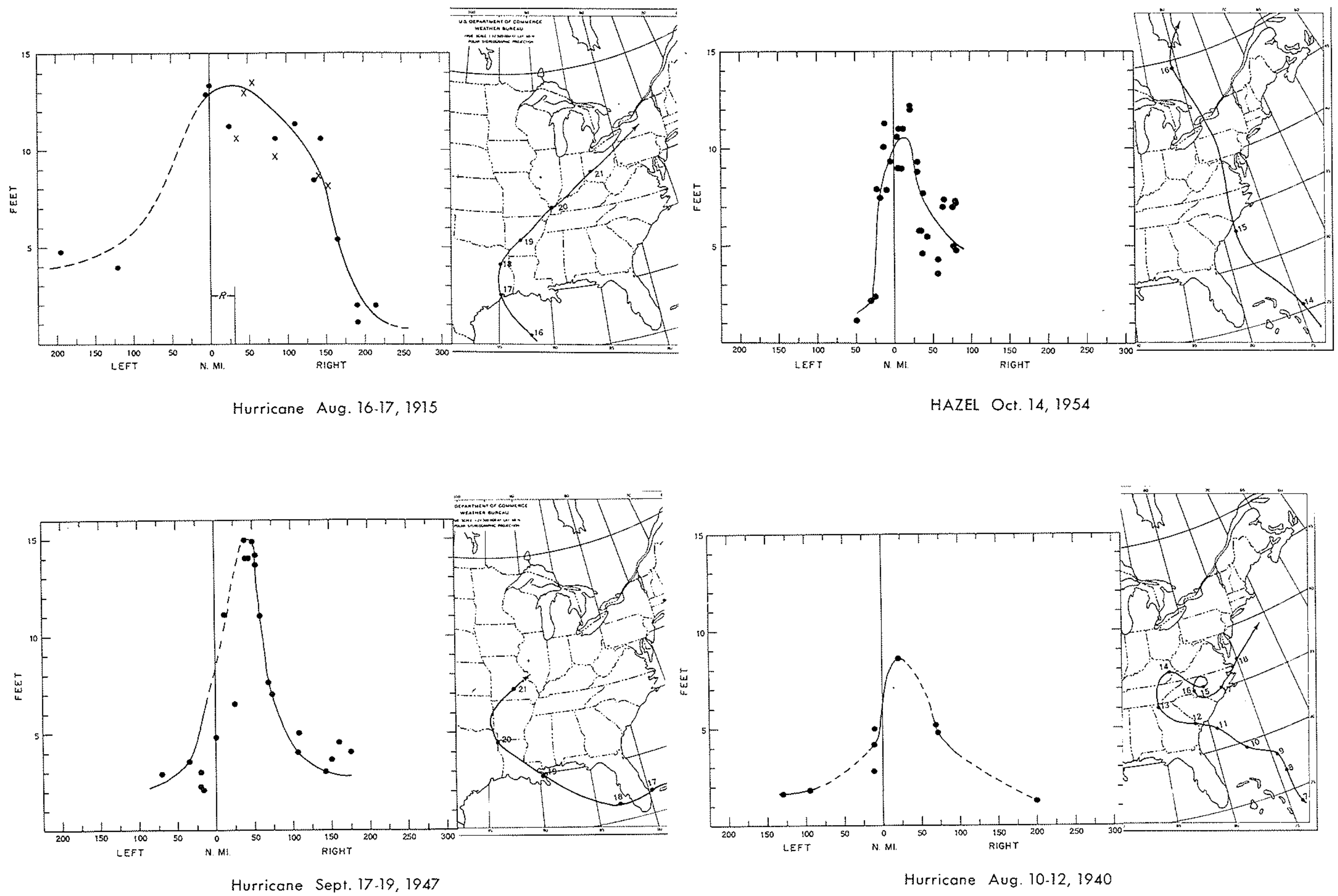


Figure 78. - Examples of storm surge profiles along the coast. (After Harris [41].)

closed form. The existing solutions have all been derived by idealizing the problem in some way. An analytic solution can be obtained most readily by assuming that the sea is a rectangular lake of constant depth on a non-rotating earth, and the solution obtained in this way will have a close resemblance to the true solution in a great many cases. For other problems it may be better to assume that the sea is unbounded, or that the sea has only one boundary, and the depth increases at a constant rate as one leaves the shore. The simplest solutions are obtained by assuming that flow can take place in only one horizontal direction. Solutions obtained in this way will sometimes give excellent results for the storm surge generated in a long, narrow lake or for the advection of a storm surge in a river or other narrow channel. Even in the great majority of cases in which flow is not one-dimensional, the one-dimensional equations will reveal many of the major factors involved in storm surge generation.

If a steady wind blows parallel to the axis of a narrow channel long enough for equilibrium conditions to develop, the differential equation for the slope of the free surface, as derived by Keulegan [75], is

$$\frac{\partial h}{\partial x} = \frac{\rho_a}{\rho_w} \frac{\gamma^2 V^2}{g (H + h)} \qquad (6)$$

where h is the height of water surface above the equilibrium; x is the distance along the axis of the channel, with the wind blowing toward positive x; ρ_a is the density of the air; ρ_w is the density of water; γ^2 is the wind stress coefficient, approximately 2×10^{-3}; V is the wind speed; H is the equilibrium depth of the water when no wind is blowing; and g is the acceleration of gravity.

The total storm surge height due to the wind (frequently called wind setup) can be obtained in this simple model by integrating equation (6) from a fixed boundary, or from a position at which, due to a low value for V or a high value for H, the slope is virtually zero.

Although this simple situation rarely exists in nature, this equation does serve to show that the slope of the free surface is related directly to the square of the wind speed and inversely to the total depth of water. This suggests that a given wind condition may produce a slightly lower storm surge if it occurs at high tide than if it occurs at low tide. This deduction is supported by observations [133]. Equation (6) also indicates, other conditions being equal, that the highest surges will occur in regions in which the wind has a long fetch over relatively shallow water. This also is generally supported by observations, but sufficient data to establish this empirically for hurricane conditions over open water are not available.

Several empirical studies have shown a reasonably good fit between the slope of the water surface and some power of V different from 2 [21, 47]. The factor γ^2 is related to surface roughness of the water, that is, to the wave height and wave velocity relative to the wind. Neumann [108] has suggested that this would actually lead to a decrease in γ^2 with increasing wind velocity and therefore effectively to an exponent of V less than 2. Reid [122] has shown that an exponent of V different from 2 may arise even though γ^2 is assumed to be constant, because of the laws governing V and H in the particular case. It is also likely that the data developed in many empirical studies, involving only a few cases and a restricted range of velocities, will fit a linear law as well as they do a square law.

Although equation (6) will sometimes give a valid representation of the storm surge in a lake or bay, it is necessary to consider several other factors in order to explain the storm surge which develops along the open coast. The finite size of the storm is clearly important. If the storm were stationary and no flow parallel to the shore were possible, the wind effect at any point on the shore would be a function only of the wind stress seaward of that point, and the profile of the peak storm surge values would approximately coincide with the profile of the wind stress component perpendicular to the shore. If flow parallel to the shore occurs (assuming the storm is still stationary) the peak would be somewhat flattened. Gradients in water elevation brought about by variations in wind strength parallel to the shore would reduce the water level below its equilibrium value near the peak winds and lift it above its equilibrium at some distance to either side of the peak. The component of wind stress parallel to the shore would also generate an alongshore component of the ocean current. The Coriolis force generated by an alongshore current would cause an increase in water level to the right of the current. The decrease in pressure in such a stationary storm would be compensated for by an increase in water level of approximately one foot of water for each one inch depression in the barometric pressure. All of these effects will also be present in a moving storm, but in many cases the disturbing forces will not last long enough to permit equilibrium values to be obtained. In others, the effects of resonance will lead to the development of heights above the equilibrium value.

The influences of these dynamic factors are well illustrated by the storm surge curve for Galveston during hurricane Audrey, June 1957 (fig.79).

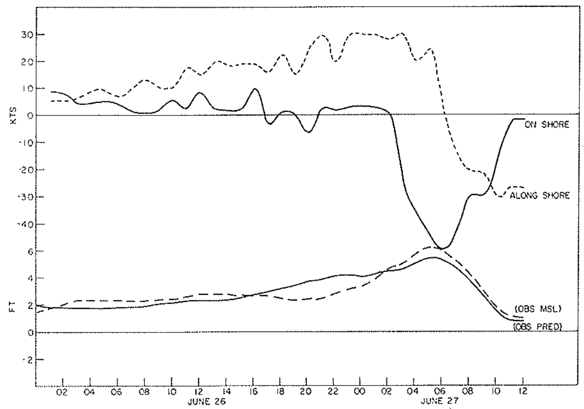


Figure 79. - Tide and wind records at Galveston, Texas during hurricane Audrey, 1957. Bottom: dashed line, tide height above mean sea level; solid line, storm surge. Top: dashed line, component of wind parallel to shore (positive when shore is to right of wind vector); solid line, component of wind perpendicular to shore (positive when wind is blowing onshore).

Note that the wind had an offshore component during most of the period of increasing storm surge. Although the wind data used here are those observed at the Weather Bureau Airport Station in Galveston, they should be generally representative of the winds for a considerable area around Galveston during this storm. This figure indicates that the water level at Galveston was not controlled by onshore winds alone. The increase in water level seems to be better associated with strong, alongshore wind components. This suggests that the high tides recorded near Galveston, on the channel side of the island, were due either to piling up of Galveston Bay water near the tide gage, with no inflow from the Gulf, or to a tendency for piling up of water to the right of the wind due to Coriolis force. No data are available to clearly distinguish between these two hypotheses, and it is conceivable that both mechanisms were operating. Also it is likely that boundary effects of the Louisiana and Texas coasts contributed to the buildup of the storm surge in this case.

Freeman, Baer, and Jung [31] have proposed a system for computing the effects of the Coriolis force due to the alongshore component of the wind, and the direct effect of the onshore component of the wind in piling up water against the shore. This system, which is based on fundamental principles, does predict surge heights which are well within the proper order of magnitude. However, it does not take into account all of the dynamic effects which are believed to be important and moreover requires a more detailed specification of the wind field while the storm is still at sea than it is possible to give at the present time.

The Effects of Local Topography

It is often useful to think of the storm surge as a wave-like disturbance of the sea surface in which the wavelength is of the order of 100 mi and the period between 8 and 24 hr. Considered in this way, it is easy to see that the surge height experienced on the open shore can be greatly modified as it moves through a bay or a river. The amplitude of the disturbance will frequently double within a distance of only a few miles as it progresses into a bay with converging shorelines. Likewise the height of the disturbance may be decreased near the middle of a wide bay with only a narrow connection with the sea. Figure 80 shows many of the complex effects of local topography on the storm surge produced by hurricane Carol of 1954.

If the storm tide at the coast rises above the top of the barrier islands, the water will flow directly inland with little regard to the natural drainage channels. In these cases the peak tide levels are to be expected a short distance inland from the natural coast and will then slope downward inland. This peak will occur landward of the natural shore because the presence of the submerged coastline will have little effect on the slope of the free surface of the water. The slope downward at points farther inland will occur because the inertia of the water and the effects of friction as the water flows over vegetation will prevent the transport of enough water inland to maintain an equilibrium between the moving storm and the slope of the free water surface. This effect is shown by the record of peak tides produced by hurricane Audrey of 1957 (fig. 81). No land remained above water south of the intracoastal waterway at the height of the storm tide. In some areas the storm tide extended far beyond this canal and in others the spoil banks formed in building the canal served as dikes to impede the northward flow of water. These dikes had to be breached at several places to permit the land to drain after the storm.

The direct effect of wind stress over an enclosed or semi-enclosed body of water is to pile up water at the leeward end of the basin. This effect is nearly independent of the advection of the surge from the open sea into the basin. A wind blowing from the sea toward the head of a bay will serve to increase the surge height at the head of the bay. A wind blowing toward the sea will tend to decrease the water level at the head of the bay, but it may not overcome the effects of the progressive surge.

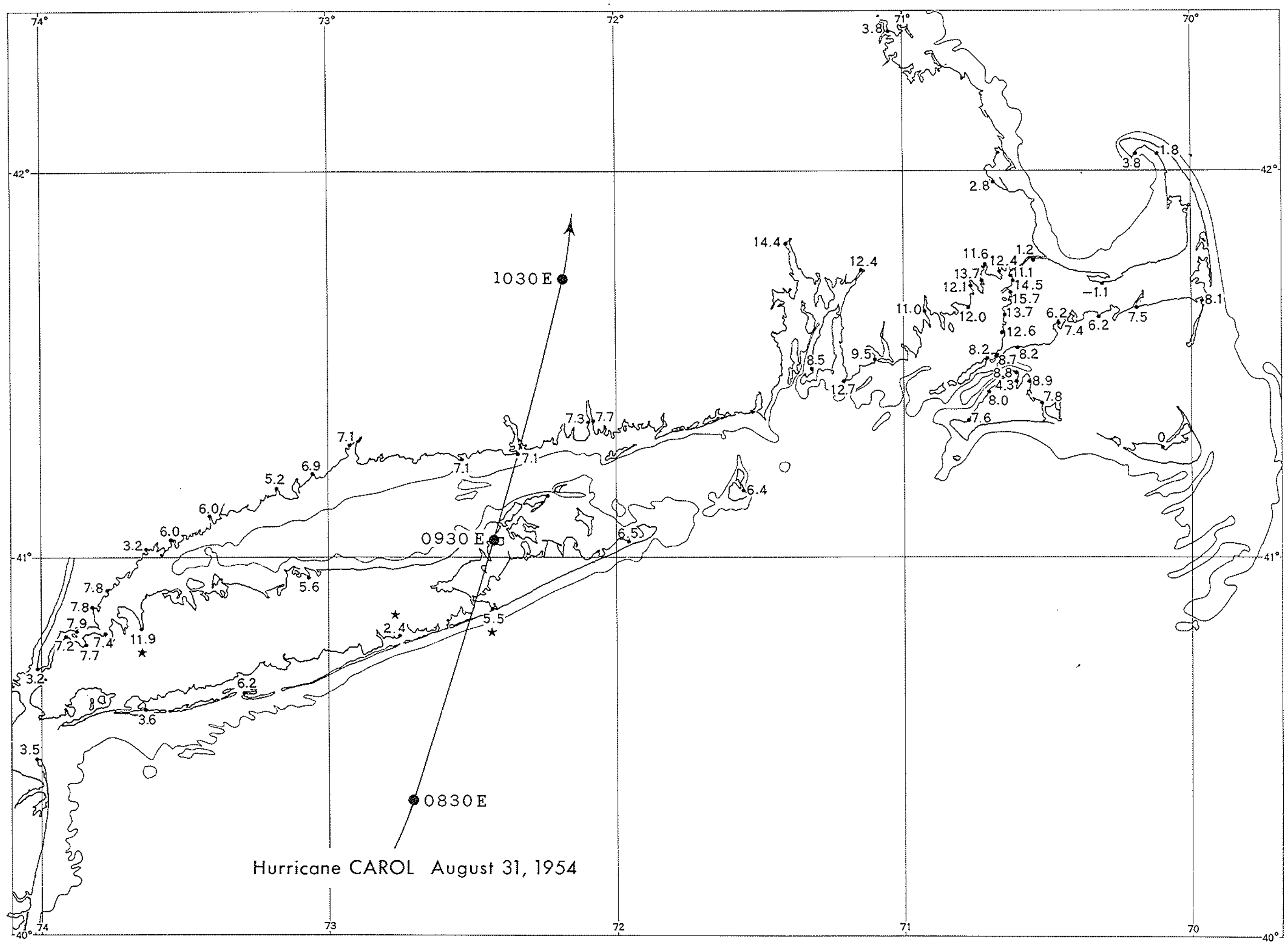


Figure 80. - Heights of storm surge associated with the landfall of hurricane Carol, 1954. The peak storm surge observed at each station is shown to the nearest tenth of a foot. At most recording tide stations the peak storm surge coincided in time with the normal high tide. This is assumed to hold true at stations where only high water data were available. At starred locations normal tide values were unobtainable and values shown represent the peak storm tides. (After Harris [41].)

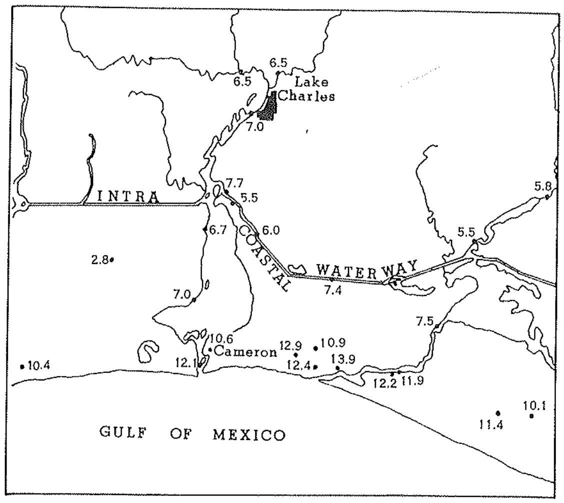


Figure 81. - Storm tide elevations in the vicinity of hurricane Audrey, June 1957. All elevations are expressed to the nearest tenth of a foot above mean sea level. Data obtained, U.S. Army Corps of Engineers, New Orleans District, and State of Louisiana, Department of Public Works.

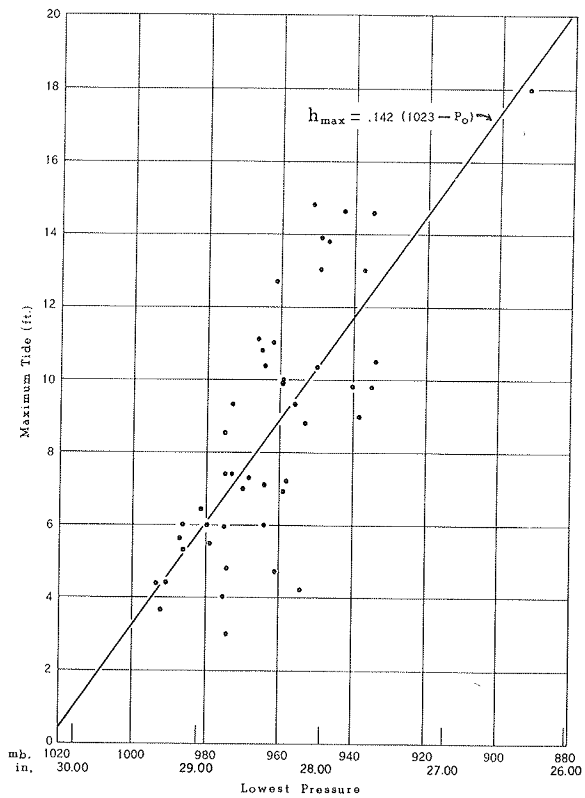


Figure 82. - Peak storm surge height as a function of minimum central pressure of hurricanes. (After Conner, Kraft, and Harris [18].)

Effects of Waves and Swell

In addition to the direct effects of wind stresses and the progression of the surge into bays, there is another important effect due to the transport of water by wave action. Wave motion in deep water is largely oscillatory and very little water is carried forward. However, in shallow water the forward velocity in the crests exceeds the backward velocity in the troughs so that a progressive motion of water toward the shore is maintained. This is accentuated by waves breaking over a reef or in the shallow region near the shore, and by wave run-up at the beach or waves splashing over a sea wall. Although this effect is not well understood, it is believed to be largely controlled by the topography within a mile or so of the place of observation. Thus, water transport by waves is quite variable along the coast and will always lead to development of high water marks on shore, which are higher than the highest point on the record of any nearby tide gage. This may lead to the development of a very ragged high water line, in which peak tide elevations differ by 2 or 3 ft in as many miles. This effect clearly limits the accuracy of high tide forecasts which are possible for any extensive stretch of coastline.

In the immediate neighborhood of the coast, and in the flooded region, the most damaging hurricane inundation arises from swell and individual, short-period waves. These may be prominent along the coast many hundreds of miles from the storm. The wave height in the open sea is a function of the wind speed, the fetch (the length of the region in which the wind direction is essentially constant), and the duration (length of time the wind blows over the fetch). Near the coast the bottom topography becomes important and may dominate the other factors in hurricane conditions. The most important factor limiting the wave height in the flooded region may be the depth of the water. Studies of waves breaking in shallow water indicate that the maximum wave height, trough to crest, will rarely exceed 0.78 times the still water depth [97]. The still water depth referred to here is the depth of water as averaged over several wave periods. For example, if the storm tide reaches a level of 8 ft MSL, in a region in which the land elevation is 3 ft MSL, the water depth will be 5 ft, and the maximum wave height will be approximately 4 ft. Since about 90 percent of the wave height in shallow water is above the still water level [97], waves could bring the total water depth to about 8.5 ft above the land elevation in this example.

Waves running up along a sloping beach may be somewhat higher than that indicated above.

Detailed studies by coastal engineers may show a lower limiting wave height at some coastal locations. However, in the absence of such studies, it is recommended that waves of the limiting height shown above, be assumed in making plans for hurricane preparedness. Warnings of high waves should be included in warnings of hurricane storm surge conditions but quantitative forecasts of specific wave heights to be expected under these conditions are not warranted at the present time.

Empirical Forecasting Aids

Since the dynamical models of storm surge generation are either greatly over-simplified or too complicated for ready use in the field, and since in either case they are rather uncertain, it is necessary to consider empirical correlations between other, more easily observed, hurricane parameters and the associated storm surge. Accounts of two such studies, one by Conner, Kraft, and Harris [18] and the other by Hoover [53], have recently been published. Figure 81 taken from [18], shows the correlation between the minimum pressure, as determined by the methods described by Myers [99], and the highest reported storm tide along the coast of the Gulf of Mexico or estimated highest storm surge along the coast of the Atlantic Ocean. An effort was made to eliminate the effects of local topography as discussed above. However, no effort has been made to eliminate the effects of variations in the annual or seasonal average level of the sea, or the effects of wave setup. Some of the storm surge data may be subject to the uncertainty indicated in figure 76. The correlation between the central pressure and the peak storm surge along the Atlantic coast, or peak storm tide in the Gulf of Mexico, is about 0.70, indicating that approximately half of the total variability in the peak storm surge height on the open coast can be explained by variations in the intensity of the storm. A further analysis of the data fails to show any statistically significant relationship between the residuals derived from the above study and the slope of the continental shelf, the speed of the storm, the size of the storm, or the pressure at the edge of the storm. Thus it appears that the random variability arising from wave setup, variations in sea level, and variations in timing, as shown in figure 76, are more important in these data than the systematic effects of local topography and other storm parameters.

In future applications of this forecasting technique it would be desirable to take variations in sea level and tide level into account by adding the mean level for the week or two preceding the hurricane and the predicted normal tide elevations to the surge height determined from the regression line in figure 82. No suggestions for considering the other variables can be offered at this time.

APPENDIX I

AN EXAMPLE OF THE RIEHL–HAGGARD–SANBORN METHOD FOR PREDICTING THE 24-HOUR MOVEMENT OF A HURRICANE

EQUATIONS FOR PREDICTING STORM MOTION

The 24-hr movement of a hurricane as predicted by the method developed by Riehl, Haggard, and Sanborn [127] requires the evaluation of regression equations as follows:

$$C_n = 0.8 + 1.2\ G_n \tag{7}$$

for meridional motion,

$$C_w = 0.96\ G_w + 0.02\ G_w^2 \tag{8}$$

for the eastward motion, and

$$C_w = G_w \tag{9}$$

for westward motion. In these equations C_n and C_w are the meridional and zonal components of the storm motion, respectively, and G_n and G_w are the corresponding 500-mb geostrophic flow components. The units in (7) are deg lat/day and those in (8) and (9) are deg long/day.

CALCULATION PROCEDURE

The procedures for evaluating the meridional and zonal components as described in [127] are quoted below. (The diagram in figure 83 is figure 1 of the reference and is used in the computational procedure.)

"Meridional Component.—(1.) The current surface-center position is marked on the 500-mb chart. The meridians 7.5 deg long east and west of the center are located. On both meridians, five points are marked at intervals of 2.5 deg lat, from 5° N to 5° S of the latitude of the storm. This determines the minimum area of influence.

"(2.) The mean 500-mb height difference between the two meridians is calculated (east minus west) and converted to height difference in feet per 5 deg long. One then enters figure 1 [fig. 83 here] at the mid-latitude of the grid and moves left (positive height difference for northward geostrophic component) or right (negative height difference for southward geostrophic component) to the observed height difference, then upward to the meridional displacement scale at the top of the diagram. This yields the first approximation of the meridional component of motion in degrees of latitude per 24 hr.

"(3.) If the area influencing the meridional displacement extends 5 deg lat beyond the center position as assumed here, the calculation just described will not suffice for storms that move northward rapidly. For instance, if a storm moves 5 deg lat in 24 hr, its movement will take place under the influence of the region up to 10 deg lat north of the initial position, and this should be considered in the forecast. If it moves only 1 deg lat in 24 hr, however, the region of influence will remain confined to the initial grid.

"Based on this reasoning, a stepwise procedure is initiated. If the first calculation indicates a motion that will carry the storm more than halfway to the latitude of the nearest grid point north of the storm, the grid is expanded for a second approximation. Since the grid points are spaced 2.5 deg lat apart, this means that if the first approximation yields a movement of 1.3 deg lat or more, two grid points located 7.5 deg lat north of the center are added on the boundary meridians, and their 500-mb heights are incorporated in the calculation. If the motion computed initially is more than 3.7 deg lat, by the same geometry, points 7.5 and and 10 deg lat north of the center are included. The following table illustrates the scheme further:

Initial calculation (deg lat/day)	Grid points added north of center
up to 1.2	none
1.3–3.7	7.5°
3.8–6.2	7.5 and 10°
6.3–8.7	7.5, 10 and 12.5°
etc.	

"Suppose now that the initial approximation yields 5 deg lat and that the second approximation, made with the grid expanded to 10° N of the center, yields not more than 6.2 deg lat. The calculation is then stabilized, and the displacement obtained from the second approximation is the forecast. If the second approximation results in a movement of more than 6.2 deg lat, a third approximation with further grid expansion becomes necessary. The procedure continues until the calculation stabilizes. In practice, three approximations will suffice in almost all instances.

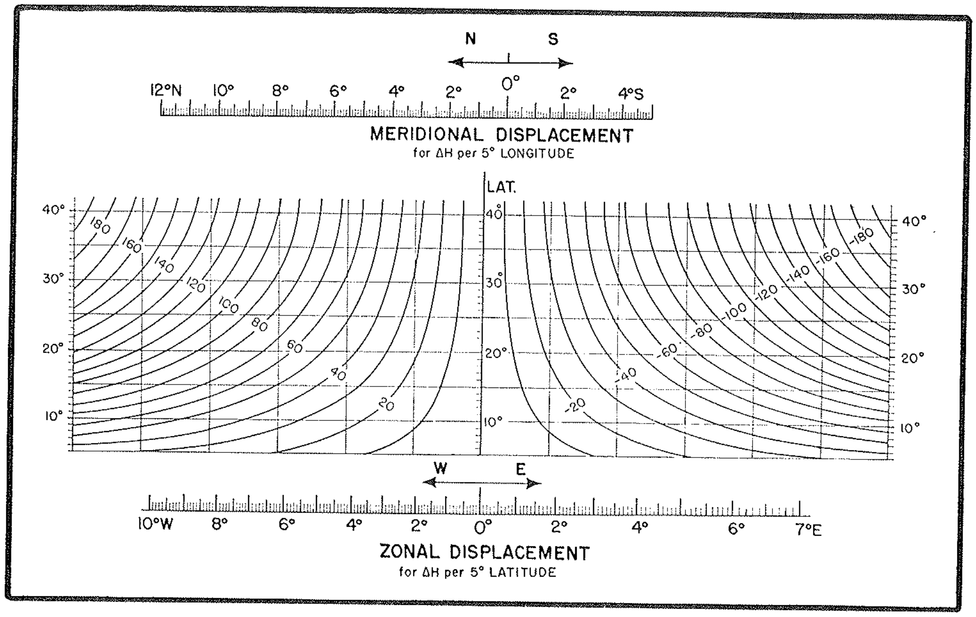


Figure 83.—Diagram for calculation of meridional and zonal components of 24-hr storm displacement. (After Riehl, Haggard, and Sanborn [127] .)

"(4.) There are several special situations which, based on experience gained during the experiment, are best dealt with as follows:

(a.) Only one approximation is made when the displacement is southward.

(b.) If the sense of the east-west height gradient reverses between the storm latitude and 5 deg lat to the south, the lowest latitude is omitted from the calculation.

(c.) If the second or third approximations reach into a belt where the sense of the east-west height gradient reverses from that existing closer to the storm, the calculation is terminated.

(d.) If the east-west extent of the grid reaches beyond a trough or ridge line in the wave pattern of the basic current, the grid should be contracted to coincide with the trough or ridge line to obtain the full measure of the intensity of the steering circulations.

"Zonal Component.—(1.) After completion of the meridional component, points are marked on the 500-mb chart on the meridians 7.5 and 2.5 deg long east and west of the center, 5 deg south of the initial storm position and 5 deg lat north of the final storm position. However, again on the basis of experience, the grid should not be extended beyond 10 deg lat north of the initial storm position.

"(2.) The mean 500-mb height difference between the two parallels is determined (north minus south) and converted to height difference in feet per 5 deg lat. One then enters figure 1 [fig. 83] at the mid-latitude of the grid, moves left (positive height difference for westward geostrophic component) or right (negative height difference for eastward geostrophic component) to the observed height difference, and then downward to the zonal displacement scale at the bottom of the diagram. This yields the zonal component of storm displacement in degrees longitude per day. Even though a storm may move to the edge of the grid in 24 hr, it has not proved necessary to apply stepwise approximations."

FORECASTING EXAMPLE

It is recognized by those who use the method that the forecast values are sensitive to small changes in the 500-mb analysis. This example will be presented to illustrate a technique using differential analysis to produce an improved 500-

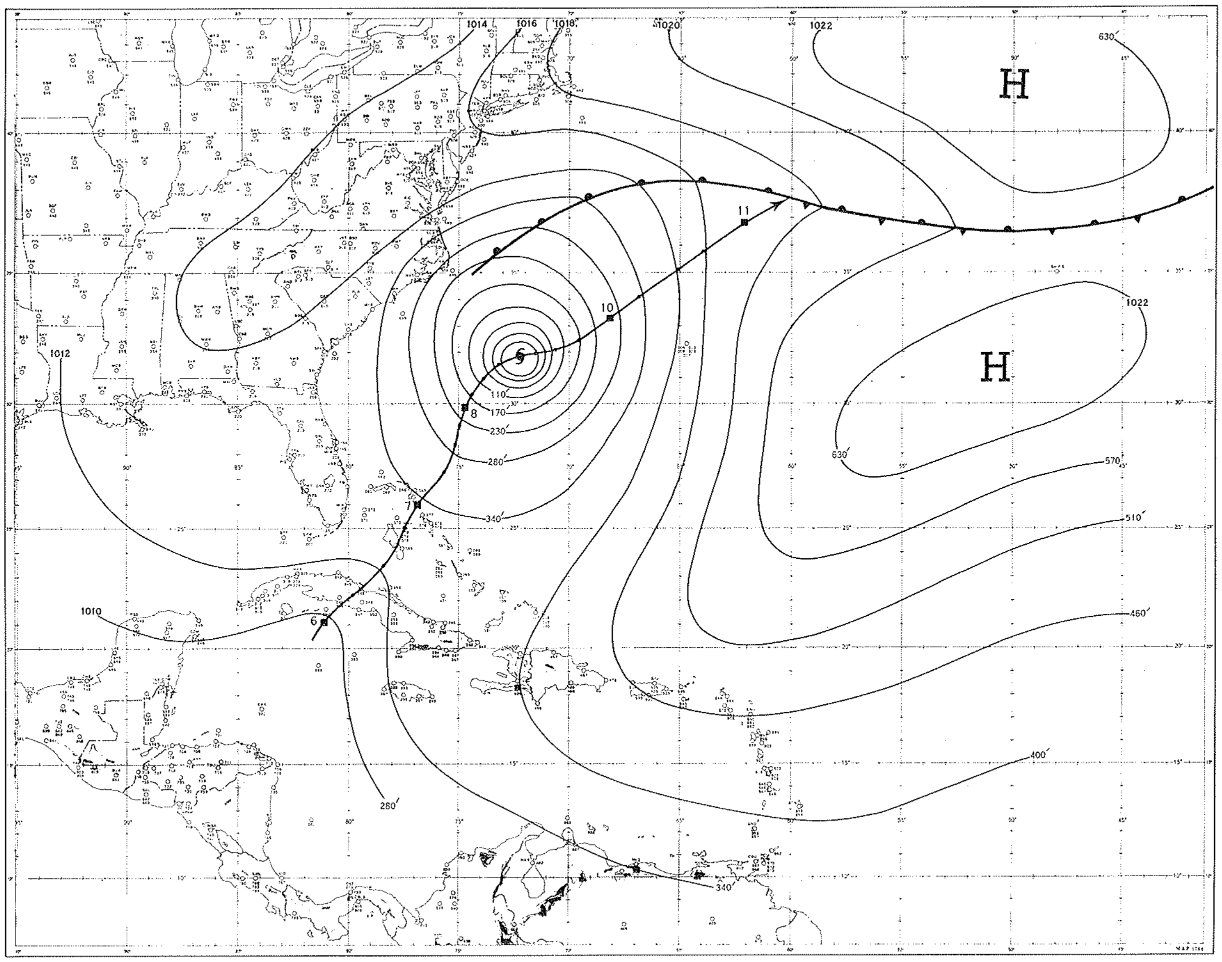


Figure 84.—Sea-level chart, 0000 GMT, October 9, 1958, showing hurricane Janice and its track. Squares with accompanying numbers along track show 0000 GMT positions for the days preceding and following October 9; dots show other 6-hourly positions. Isobars are labeled in mb and in terms of 1000-mb heights.

mb chart which apparently is essential for the success of the method.

The example selected is hurricane Janice for the 24-hr period, October 9-10, 1958. This storm had moved northeastward out of the Caribbean, and as it approached latitude 30°N began to reduce this forward motion and assume a more northerly track. At 0000 GMT on October 9, the storm had begun moving east-northeast with some initial acceleration and with no observational evidence that further acceleration should not be expected. However, it proceeded east-northeastward at an average rate of less than 10 kt for the period of this computation.

The effective application of the Riehl-Haggard-Sanborn technique requires some systematic effort to develop the best possible 500-mb analysis. Since there normally is at least an order of magnitude more observational data at the surface than at 500 mb, the most effective and practical means of accomplishing the differential analysis is to begin by performing the best possible surface analysis. The surface analysis for 0000 GMT, October 9, is given in figure 84. The analysis has been carried out for even-numbered isobars and relabeled in terms of 1000-mb heights based on the tropical standard atmosphere. The second step is then to construct an independent 500-mb

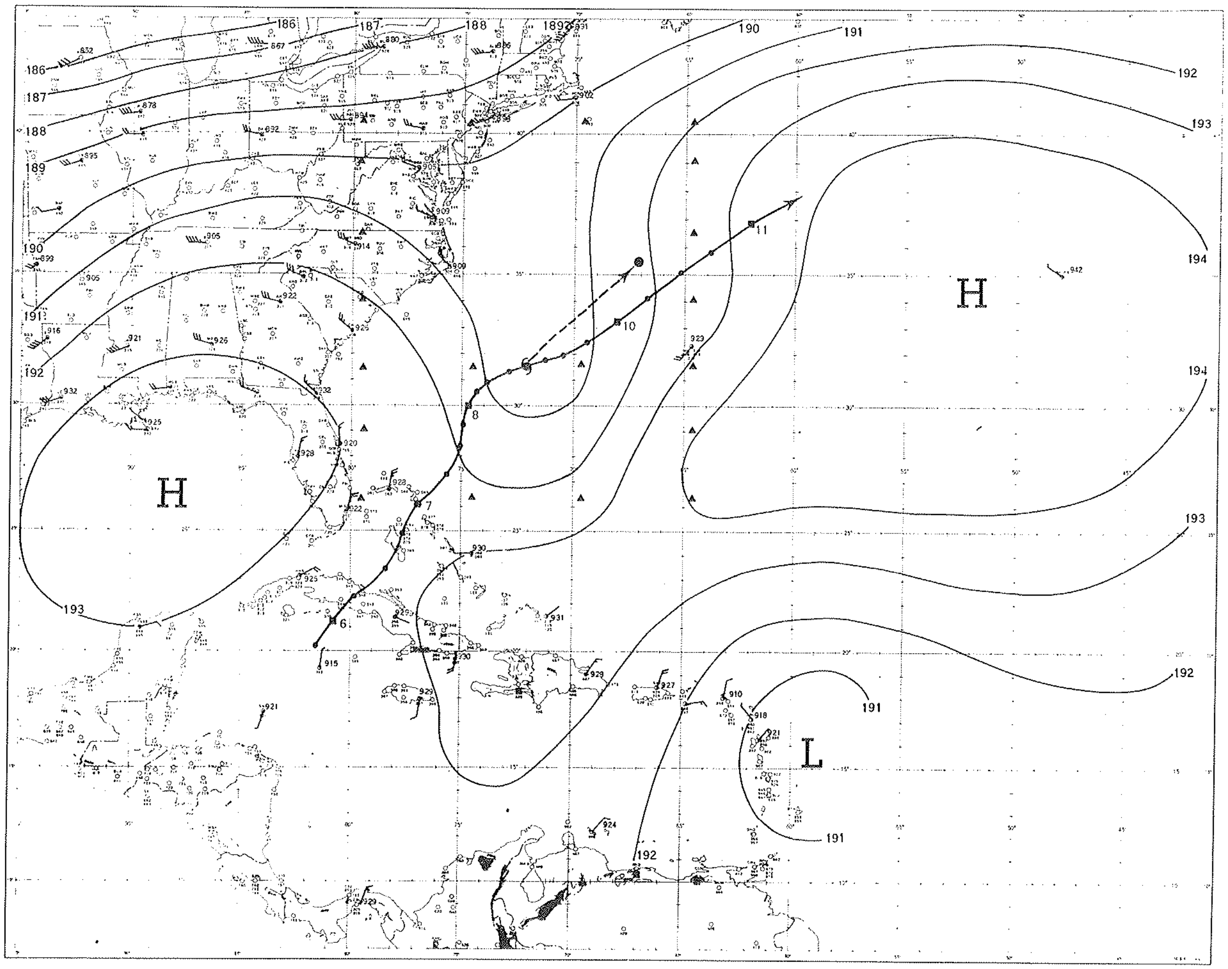


Figure 85.—Preliminary 500-mb analysis based upon continuity and 500-mb data alone, 0000 GMT, October 9, 1958. Computational grid points are indicated by solid triangles. Dashed arrow shows 24-hr displacement using Riehl-Haggard-Sanborn method applied to this chart. This predicted position was in error by 140 naut mi. Track of Janice is indicated as in figure 84.

analysis using the best possible time continuity, and in tropical regions giving more weight to wind direction than to contour heights. Care should be taken to assure that when the placement of a contour is made on the basis of a wind report at the expense of a height report, there is vertical consistency of the winds at the station. Figure 85 gives such an analysis. With so little information normally available over ocean areas, there is always more than one reasonable solution to the analysis at the 500-mb level based on the reports at that level alone. It should not be surprising, therefore, that a computation from the Riehl-Haggard-Sanborn grid on such a chart as this frequently gives quite large errors. In the case of this analysis, the 24-hr computational error is 140 naut mi.

The next and most important step is to compute the thickness between the 1000 and 500-mb charts for individual stations and 5 deg intersections of latitude and longitude over the ocean areas. This has been done as a first step in figure 86. Ideally, wind shear vectors for the layer 1000-500 mb should be computed as a guide in drawing the thickness isopleths. However, once good continuity has been established, there is sufficient conservation of isotherm patterns that it is not generally necessary to continue computing these

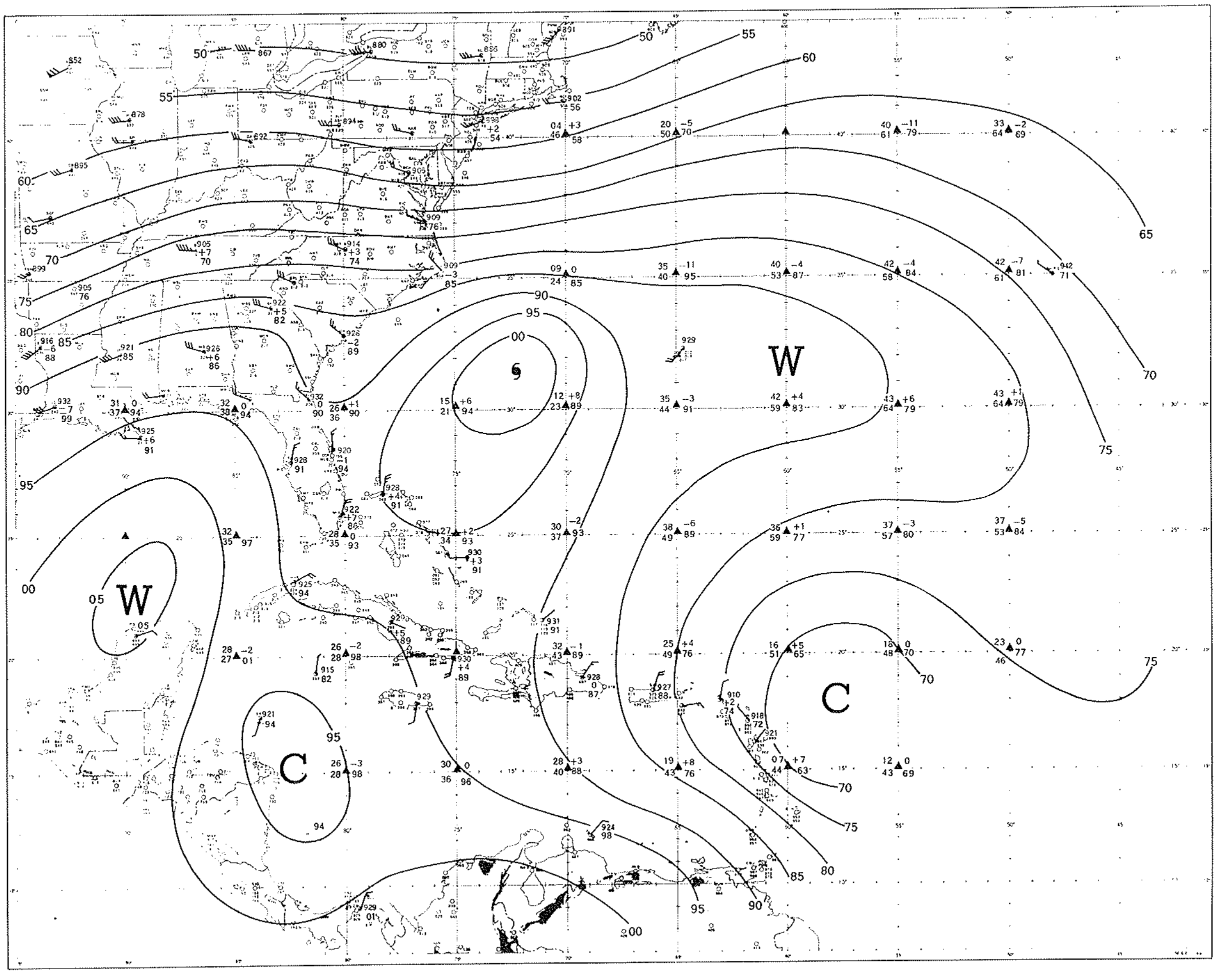


Figure 86.—Thickness (1000-500 mb) analysis, 0000 GMT, October 9, 1958. At latitude-longitude intersections, interpolated 500-mb heights from analysis in figure 85 are shown at upper left, 1000-mb heights at lower left, thicknesses obtained from these at lower right (all in 100's and 10's of ft), and corrections to the thicknesses and 500-mb heights as derived from the thickness analysis at upper right (in 10's of ft). At radiosonde stations observed height, correction, and original thickness are given to right of station.

vectors. The next step is to sketch in a field of isotherms beginning at the edges of the chart and working inward toward the storm center, spacing the isotherms primarily on the basis of reported thicknesses at observing stations. In the vicinity of the storm, considerable care must be exerted to avoid extreme contrasts, and preserve the proper shape of the isotherms. The following guidelines will be helpful in this regard:

(1) In the subtropical ridge to the east or north of the storm, the thickness is generally between 18,800 and 18,900 ft, except somewhat lower north of latitude 35° and somewhat higher south of latitude 20°.

(2) Along the subtropical ridge there is normally very little gradient of thickness (1000 to 500 mb).

(3) The hurricane invariably lies in a pool of warm air open to the south or southwest.

(4) In the moving storm the isopleths which enclose the storm are elliptical with major axis oriented in the general direction of motion of the storm.

(5) In all but immature storms the 19,000-ft

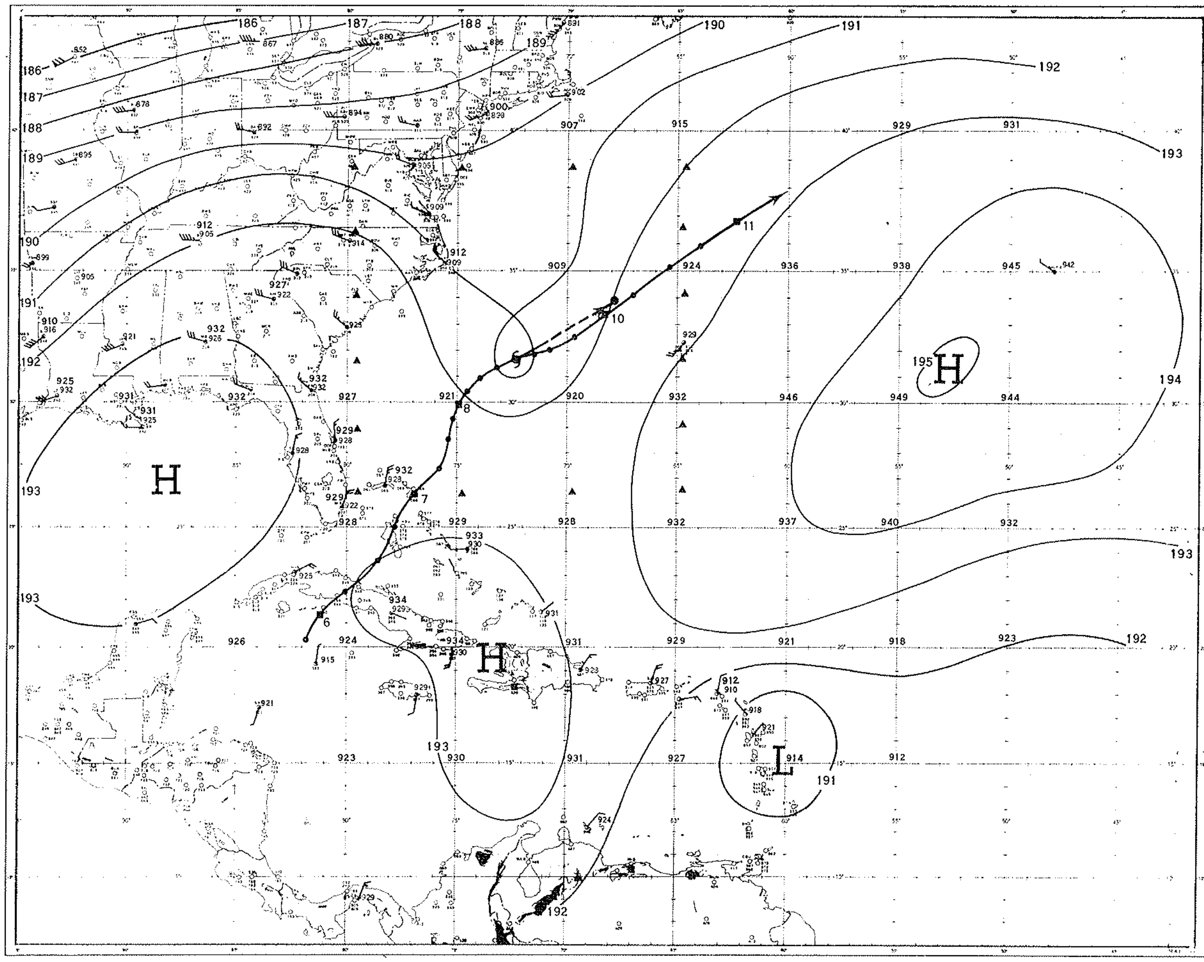


Figure 87.—Final 500-mb analysis, 0000 GMT, October 9, 1958, based on thickness analysis corrections shown in figure 86. Corrected 500-mb heights are given by larger numbers at radiosonde stations and at grid points. Dashed arrow shows 24-hr displacement using Riehl-Haggard-Sanborn method applied to this chart. This predicted position was in error by 38 naut mi. Track of Janice and computational grid are indicated as in figure 84.

thickness line encircles the center at a minimum radius of 1 to 2 deg.

Once a reasonable thickness pattern has been established, the next step is to correct the computed thicknesses first at 5 deg intersection points, and, finally, at those reporting stations where the pattern cannot be made to conform. The corrections to the computed thickness are then added algebraically to the observed or computed heights of the 500-mb surface and the corrected heights recorded on a fresh chart or overlay sheet. The final analysis of the 500-mb chart is then constructed adhering quite literally to the corrected height values. This analysis then becomes the basis for the final computation of movement. Figure 87 is the final analysis for this particular example. This solution presents quite a different picture of the circulation influencing the storm movement. A computation from this chart gives a 24-hr error of only 38 naut mi. A summary of the movement of the storm and the computed movements from figure 85 as a preliminary estimate and from figure 87 as a final forecast is given in table 9.

Table 9. Computed versus observed displacements of hurricane Janice, October 9-10, 1958.

Initial Position	Verifying Position	Observed Increment		Computed Increments	
				Preliminary	Final
31.6° N	33.3° N	1.7° N		3.8° N	2.2° N
72.3° W	68.2° W	4.1° E		5.0° E	4.4° E
			Error	140 naut mi	38 naut mi

The skill with which this procedure can be used is dependent directly upon the success with which the continuity is maintained, primarily in the thickness patterns for the layer 1000-500 mb. Experience at several forecast centers has shown that the expected error in computation based upon 500-mb analyses which are guided mainly by time continuity at this elevation generally average little better than the 140 naut mi attained from the analysis given in figure 85. While experience does not indicate that as much improvement can always be expected as indicated in the present case when a differential analysis technique is applied, it can be expected that results using this technique can reduce the error otherwise to be expected.

APPENDIX II

AN EXAMPLE OF SIMPSON'S USE OF WARM TONGUE STEERING IN HURRICANE PREDICTION

INTRODUCTION

The example presented here demonstrates the use of the thickness pattern between 700 and 500 mb in estimating the path (but not the speed) of a hurricane in the succeeding 24 hours [142] . One of the major problems in applying this method is that data are frequently insufficient to uniquely define the warm tongue associated with a storm.

ANALYTICAL PROCEDURE

In carrying out a warm tongue analysis, continuity is very important. The analysis should begin with the more baroclinic regions and converge gradually upon the hurricane area. As an aid in this analysis, experience has shown that it is safe to assume that

1. The hurricane will be located in an area of maximum thickness in the 700-500 mb layer,
2. For all but the most immature hurricanes the 9050-ft thickness isopleth will surround the storm with a minimum radius of approximately 1 deg lat, but only in the most mature hurricanes will the lateral displacement from the storm center be more than 2 deg lat, and
3. For a moving storm, the thickness isopleths will be extended or elongated in the direction of storm motion. The 8950-ft isopleth is ordinarily the most descriptive of the warm tongue, the axis of which tends to parallel the track or future course of the hurricane for the following 24-hr period. In some smaller hurricanes, especially as they approach a baroclinic region, the axis of the warm tongue tends to be displaced slightly to the right, but remains parallel to the storm track. In conducting the analysis very little weight should be given to shear vectors with a magnitude less than 5 kt or those which are located closer to the storm center than 3 deg lat. Shear vectors of less than 5 kt are more dependable where there is little or no change in wind direction through the layer.

Except for the reservations stated above, the drawing of isopleths should place greater weight upon shear vectors than upon thickness values at

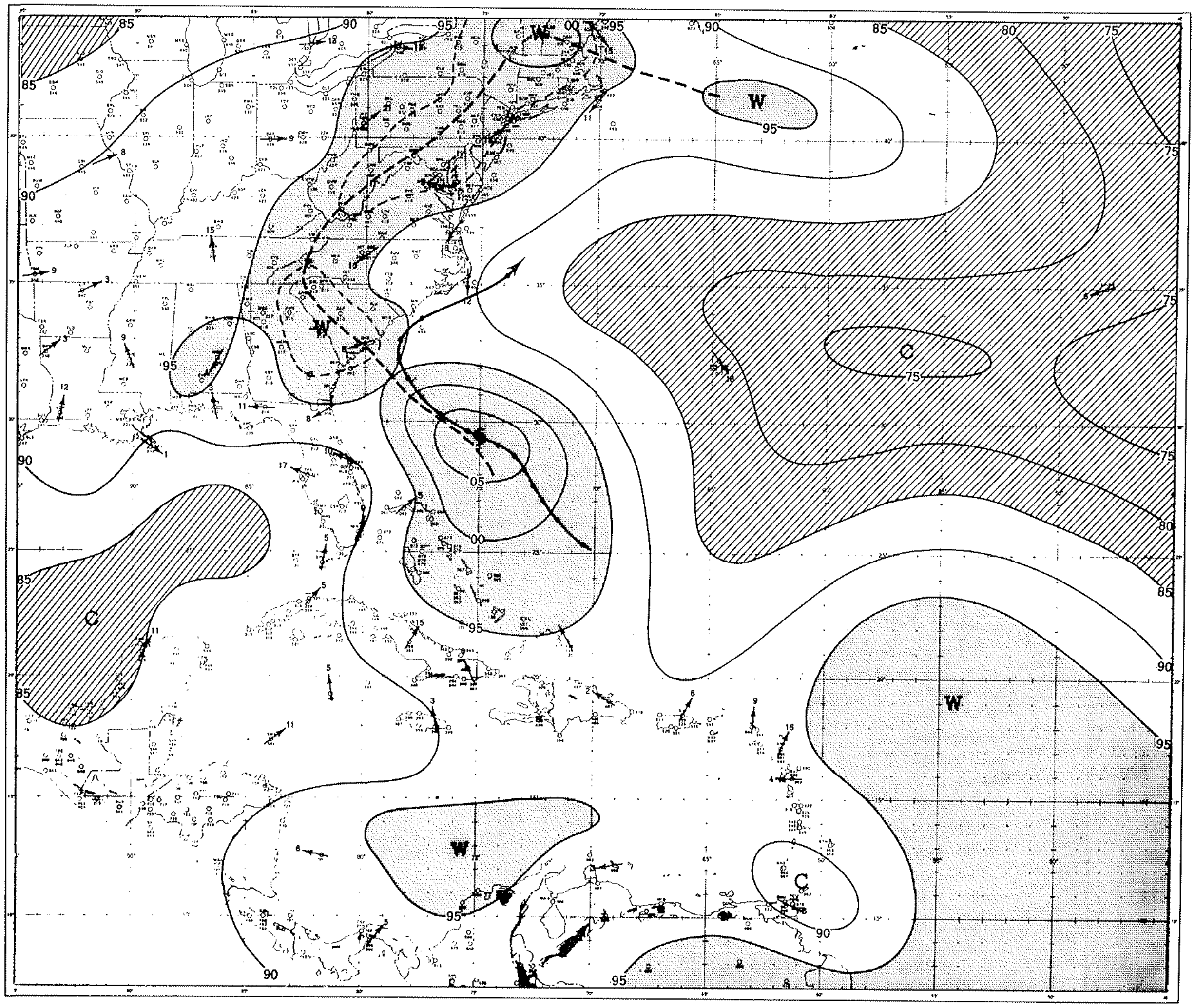


Figure 88.—Thickness (700-500 mb) analysis, 0000 GMT, September 26, 1958. Axis of warm tongue extending from hurricane Helene is indicated by heavy dashed line. Track of storm is given by solid arrowed line with dots marking 6-hourly positions. Thickness values are given in hundreds and tens of ft (8 or 9 thousand digit has been dropped from labels). Direction and magnitude (in kt) of wind shear between 700 and 500 mb are shown at observation stations.

individual reporting stations. Before accepting the latter, a careful examination should be made of the individual departures of reported 700 and 500-mb heights at a station in question from the analyzed height values at that location.

FORECASTING EXAMPLE

The example selected to illustrate warm tongue analysis as an aid in predicting hurricane movement is that of hurricane Helene on September 25 and 26, 1958. In this particular case the usefulness of the tool is well demonstrated during the most critical forecasting period. Between 0000 GMT and 1200 GMT on September 26 the changes in thermal fields along the eastern seaboard are exceptionally well indicated and there is clear evidence that the hurricane, in terms of what is known of the characteristic warm tongue, should not be expected to cross the coastline. In figure 88 (0000 GMT, September 26) it may be seen that Helene, after having moved in a general northerly course, was located in a pool of warm air which extended northwestward to an elongated zone of maximum temperatures covering the eastern seaboard. The axis of the warm tongue extended from

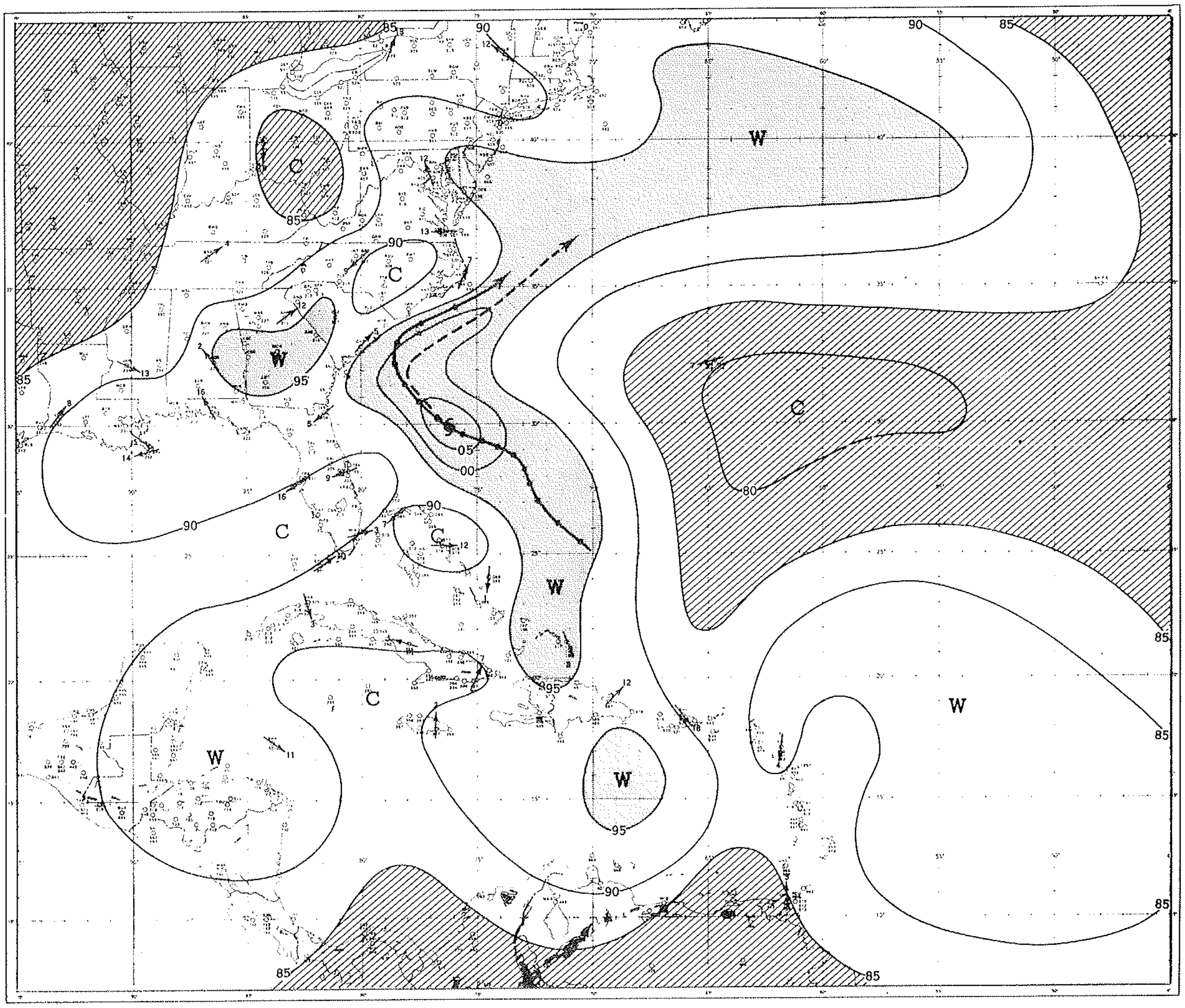


Figure 89.—Thickness (700-500 mb) analysis, 0000 GMT, September 27, 1958. See legend to figure 88.

the storm northwestward to the coast near Charleston and inland to the vicinity of Asheville, thence northeastward to Elkins, Harrisburg, and Albany. By 1200 GMT (fig. 89) the entire zone of warm temperatures had moved off the coast and the warm tongue axis indicated ultimate recurvature at a point due east of Savannah with the track remaining offshore.

APPENDIX III

AN EXAMPLE OF A 24-HOUR HURRICANE FORECAST USING THE METHOD DEVISED BY VEIGAS AND MILLER

INTRODUCTION

The prediction equations developed by Veigas and Miller [157] to forecast the 24-hr position of a hurricane consist of two regression equations for storms in the northerly zone and two for storms in the southerly zone (fig. 58). Pressure values are read from predetermined points of a grid consisting of ninety-one points located at the intersections of the latitude and longitude lines with values divisible by 5 (figs. 59 and 60). For northerly storms the grid is located so that the central point is nearest the storm center, while for southerly storms a point 5 deg lat to the south of the central point is located nearest the storm.

The prediction equations for storms located in the northerly zone (between latitudes 27.6° to 40.0°N and longitudes 65.0° to 100.0°W) are:

$$\hat{l}_{t+1} = -120.58 + 1.6620(l_{t_0}) - 0.7080(l_{t-1}) + 0.1700(P_5) - 0.0556(P_{46}) - 0.1964(P_{69}) + 0.06523(P_8) - 0.1400(P_{44}) + 0.2182(P_{42}) + 0.0586(P_{36}) \quad (10)$$

and

$$\hat{L}_{t+1} = -97.03 + 1.6676(L_{t_0}) - 0.6756(L_{t-1}) + 0.3530(P_{44}) - 0.3098(l_{t_0}) - 0.2494(P_{51}). \quad (11)$$

The prediction equations for storms located in the southerly zone (between latitudes 17.5° and 27.5° N and longitudes 65.0° and 100.0° W) are:

$$\hat{l}^*_{t+1} = -59.88 + 1.6206(l_{t_0}) - 0.5870(l_{t-1}) - 0.0327(P_{47}) + 0.2317(P_{14}) - 0.1123(P_5) - 0.2022(P_{70}) + 0.0556(P_{79}) + 0.1374(P_{35}) - 0.0606(P_{51}) + 0.0423(P_{30}) \quad (12)$$

and

$$\hat{L}^*_{t+1} = -28.73 + 1.7436(L_{t_0}) - 0.7850(L_{t-1}) - 0.0830(P_{79}) + 0.1212(P_{44}) - 0.1469(P_{66}) + 0.0600(P_3) - 0.3712(l_{t_0}) + 0.2090(l_{t-1}) + 0.0745(P_5) + 0.0395(P_{71}) + 0.1294(P_{33}) - 0.1609(P_{42}). \quad (13)$$

The symbols have the following meanings:

$\hat{l}_{t+1}$ = 24-hr predicted latitude for storm in northerly zone.

$\hat{l}^*_{t+1}$ = 24-hr predicted latitude for storm in southerly zone.

l_{t_0} = current latitude of storm.

l_{t-1} = latitude of storm 24 hr prior to time t_0.

$\hat{L}_{t+1}$ = 24-hr predicted longitude for storm in northerly zone.

$\hat{L}^*_{t+1}$ = 24-hr predicted longitude for storm in southerly zone.

L_{t_0} = current longitude of storm.

L_{t-1} = longitude of storm 24 hr prior to time t_0.

P_n = sea-level pressure at grid point n.

Points in the grid are numbered from the upper right-hand corner downward and then proceeding from east to west. Grid points used for storms in the northerly zone are given in figure 59 as circled points. Similarly, grid points used for storms in the southerly zone are given in figure 60.

FORECAST PROCEDURE

In order to evaluate equations (10) and (11) for storms in the northerly zone, the current and previous 24-hr positions of the storm in degrees latitude and longitude are required. In addition

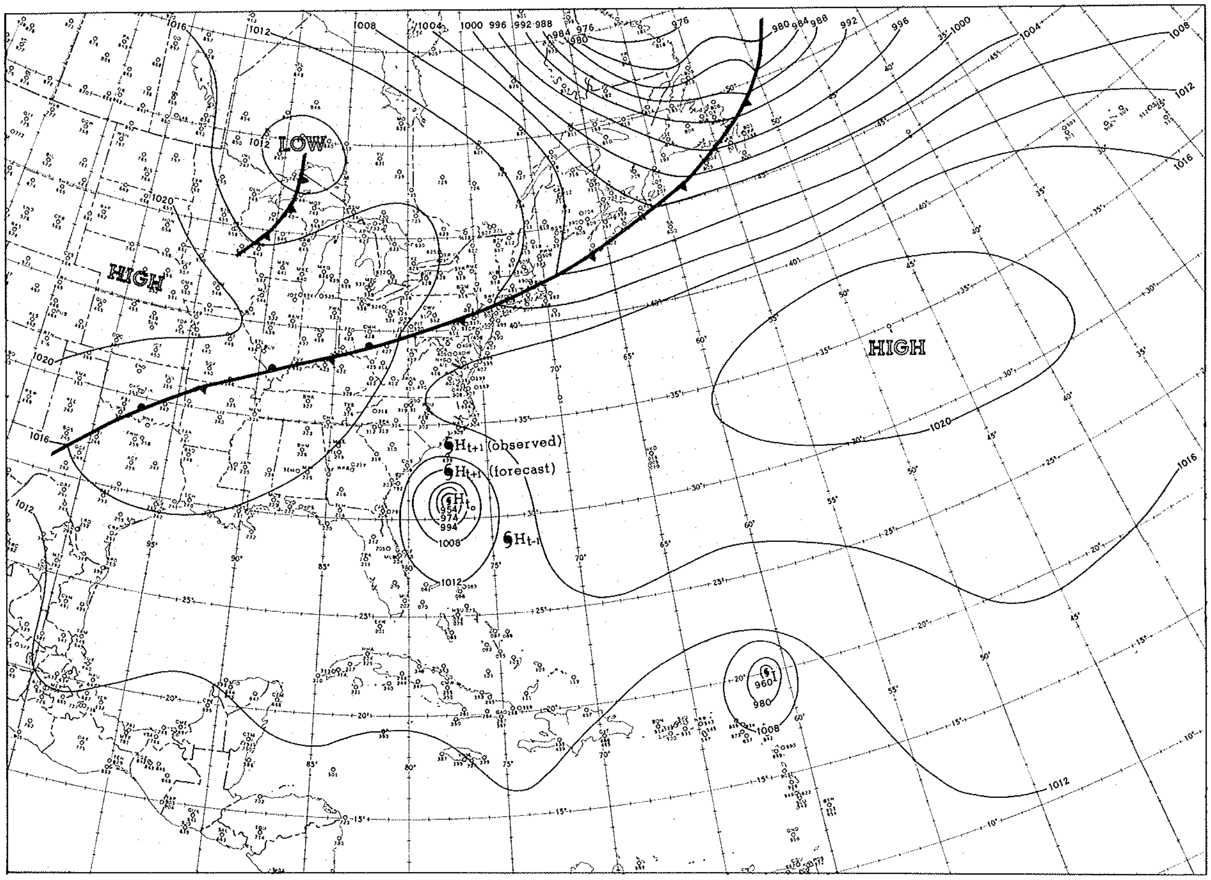


Figure 90.—Sea-level chart, 1800 GMT, September 26, 1958. Previous 24-hr position of hurricane Helene is indicated by H_{t-1}, present position by H_{t_o}, and 24-hr observed and statistically predicted positions by H_{t+1}.

the sea-level pressures at grid points 5,8,36,42, 44,46,51, and 69 are also required. Using as a reference point the central point of the grid (the point nearest the storm center), the significant pressure points are located as follows: (The location of the point is given in degrees north or south and east or west of the reference point.)

Point	Location of point
5	5S/30E
8	15N/25E
36	15N/5E
42	15S/5E
44	10N
46	0/0
51	10N/5W
69	10S/15W

Evaluation of equations (12) and (13) requires in addition to the current and previous 24-hr latitude and longitude, the surface pressures at points 3, 5,14,30,33,35,42,44,47,51,66,70, and 79. For southerly storms the reference point (the point nearest the storm center) is 5 deg south of the central grid point. The locations of points for which pressures are required are as follows:

Point	Location	Point	Location
3	10N/30E	47	0/0
5	30E	51	15N/5W
14	10S/25E	66	10N/15W
30	15N/10E	70	10S/15W
33	10E	79	15N/25W
35	10S/10E		
42	10S/5E		
44	15N		

Table 10. Corrections to be added to the predicted latitude and longitude when forecast is made from the 0600 GMT map.

Initial Latitude of Storm	Initial Longitude of Storm 100	95	90	85	80	75	70	65
40	.2	.2	.3	.3	.3	.3	.3	.3
	0	0	0	0	0	0	0	0
35	.2	.3	.3	.3	.3	.3	.4	.4
	0	.1	0	.1	.1	.1	.1	.1
30	.3	.4	.4	.5	.5	.5	.5	.5
	0	0	0	0	.1	.1	.1	.1
25	.2	.3	.4	.4	.4	.4	.4	.4
	.3	.3	.3	.3	.3	.2	.2	.2
20	.3	.3	.4	.4	.4	.4	.4	.3
	.3	.3	.3	.3	.3	.3	.2	.2

FORECAST EXAMPLE

The sea-level map for 1800 GMT, September 26, 1958, is shown in figure 90. Hurricane Helene is shown just off the south Atlantic coast. The current position of Helene is indicated by H_t and the previous position by H_{t-1}. Since the storm is located in the northerly zone, regression equations (10) and (11) are used. Data taken from the chart are as follows:

$l_{t0} = 31.0$	$P_{69} = 1011$	$P_{36} = 1011$
$l_{t-0} = 29.0$	$P_8 = 1004$	$P_{51} = 1015$
$L_{t0} = 77.4$	$P_{44} = 1014$	$P_5 = 1018$
$L_{t-1} = 74.1$	$P_{42} = 1010$	$P_{46} = 1010$

Substituting these values into the prediction equations gives $\hat{l}_{t+1} = 32.04°$ N and $\hat{L}_{t+1} = 77.18°$ W.

If the forecast is based on the 0600 GMT or 1800 GMT maps, then corrections should be made in the forecast position due to diurnal variations in pressure. Table 10 gives corrections (for the 0600 GMT map) to be added to the predicted latitude and longitude for the given position of the storm. Table 11 gives similar corrections for the 1800 GMT chart. To obtain the correction, enter table at the latitude and longitude most closely corresponding to the position of the storm at t_0. The latitude correction appears at the upper left and the longitude correction at the lower right.

From table 11, the corrections for the predicted values of latitude and longitude for hurricane Helene are +.6 deg for the latitude and 0 deg for the longitude. Thus, the corrected predicted values are 32.64°N latitude and 77.18°W longitude.

Table 11. Corrections to be added to the predicted latitude and longitude when forecast is made from the 1800 GMT map.

Initial Latitude of Storm	Initial Longitude of Storm 100	95	90	85	80	75	70	65
40	.2	.2	.2	.3	.4	.4	.4	.4
	0	0	0	0	0	0	0	0
35	.2	.3	.4	.4	.5	.4	.5	.5
	0	0	0	0	0	0	0	0
30	.3	.4	.5	.5	.6	.6	.6	.6
	0	0	0	0	.1	0	.1	.1
25	.3	.4	.5	.6	.5	.6	.5	.5
	.3	.3	.3	.3	.3	.2	.2	.2
20	.3	.4	.4	.5	.5	.5	.5	.4
	.3	.4	.3	.4	.3	.4	.4	.3

APPENDIX IV

AN EXAMPLE OF A 24-HOUR HURRICANE FORECAST USING JORGENSEN'S ORTHOGONAL POLYNOMIAL METHOD

INTRODUCTION

The use of orthogonal polynomials to derive a hurricane forecasting method has been investigated by Jorgensen [70]. The application of this method requires the evaluation of two regression equations as follows: (A somewhat simplified form of the equations is given for purposes of illustration.)

$$u = 4.182 + .8850P_u - .0171S' + 2.4187z_1' - 3.5002z_6' + 1.1835z_7' - .1537z_1 + .0909z_6 - 2.6963z_{11} \quad (14)$$

and

$$v = -2.958 + 1.3954P_v + .0084S' - 3.3073z_1' + 9.4415z_3' - 2.8165z_7' + 4.4687z_2 - 1.8975z_6. \quad (15)$$

The symbols have the following meanings:

u = forecast component of motion in east-west direction next 24 hours. (East toward west positive.)

v = forecast component of motion in south-north direction next 24 hours. (South toward north positive.)

P_u = component of motion in u direction last 12 hours.

P_v = component of motion in v direction last 12 hours.

S' = intensity of circulation parameter from 500-mb chart.

z_n' = correlation of 500-mb chart with north-south oriented mathematical surface defined by polynomial of nth degree with n taking values 1 and 3.

z_{n+5}' = correlation of 500-mb chart with east-west oriented mathematical surface defined by polynomial of nth degree with n taking values 1 and 2.

z_n = correlation of sea level chart with north-south oriented mathematical surface defined by polynomial of nth degree with n taking values 1 and 2.

z_6 = correlation of sea level chart with east-west oriented mathematical surface defined by polynomial of 6th degree.

z_{11} = correlation of sea level chart with mathematical surface defined by cross multiplication of two polynomials of the 1st degree.

PROCEDURE

Equations (14) and (15) apply to hurricanes threatening the central and north Atlantic coastal areas. The latitude degree is the unit of distance used in evaluating the components of motion. The coefficients of correlation expressed by the z's are obtained from computations performed upon data read on a seven by eight point grid on a given sea level or 500-mb chart in combination with terms of the desired polynomial. The Tschebyscheff orthogonal polynomials used in the procedure are given in table 12.

The terms of each polynomial are used to define a mathematical surface which may then be correlated with the pressure (or height) pattern as measured at the grid points of a given chart. Thus, the polynomial of the 1st degree, F_1, given in table 12, Part A, is used to define the north-south oriented surface indicated by the data in table 13. Similarly, the other orthogonal polynomials given in table 12 can be used to describe a total of six mathematical surfaces with three oriented north-south and three oriented east-west.

Additional mathematical surfaces can be defined by taking the cross product terms of any two given polynomials. Thus the cross product

Table 12. Tschebyscheff orthogonal polynomials are given through the 3rd degree. In the table the subscripts of the F's and G's indicate the degree of the polynomial. Eight terms are required for the F polynomials and seven for the G polynomials to correspond to the seven by eight point grid used. Also given are the sums of the squared terms to be used in computing the coefficients of correlation.

Part A

Polynomials used to define the north-south oriented surfaces

Term	1	2	3	4	5	6	7	8	Sum of squared terms
F_1	7	5	3	1	-1	-3	-5	-7	168
F_2	7	1	-3	-5	-5	-3	1	7	168
F_3	7	-5	-7	-3	3	7	5	-7	264

Part B

Polynomials used to define the east-west oriented surfaces

Term	G_1	G_2	G_3
1	-3	5	-1
2	-2	0	1
3	-1	-3	1
4	0	-4	0
5	1	-3	-1
6	2	0	-1
7	3	5	1
Sum of squared terms	28	84	6

Table 13. The eight terms of polynomial F_1 used to define a north-south oriented surface corresponding to the 56 points of the seven by eight point grid.

7	5	3	1	-1	-3	-5	-7
7	5	3	1	-1	-3	-5	-7
7	5	3	1	-1	-3	-5	-7
7	5	3	1	-1	-3	-5	-7
7	5	3	1	-1	-3	-5	-7
7	5	3	1	-1	-3	-5	-7
7	5	3	1	-1	-3	-5	-7

Table 14. The cross products of polynomials F_1 and G_1 which define a surface corresponding to the 56 grid points.

-21	-15	-9	-3	3	9	15	21
-14	-10	-6	-2	2	6	10	14
-7	-5	-3	-1	1	3	5	7
0	0	0	0	0	0	0	0
7	5	3	1	-1	-3	-5	-7
14	10	6	2	-2	-6	-10	-14
21	15	9	3	-3	-9	-15	-21

terms of the two polynomials of the first degree, F_1 and G_1, give the surface indicated by the data in table 14. Similarly, additional pairs of polynomials can be used to define a total of nine surfaces, although only the surface given above is used in deriving a parameter for use in the fore casting equations.

A property of an orthogonal polynomial is that the terms add up to zero. As a result, the expression for the correlation coefficient, z or z', involving the terms of a polynomial reduces to the following form:

$$z \text{ (or } z') = \frac{\Sigma XY}{\left\{\left[\Sigma X^2 - \frac{(\Sigma X)^2}{N}\right]\left[\Sigma Y^2\right]\right\}^{\frac{1}{2}}} \qquad (16)$$

where X represents the pressure (or height) value read at each grid point, Y represents the value of the term of the polynomial for the same grid point, and N equals the number of grid points with the summations taken over all 56 points. Correlations are computed from equation (16) between the sea-level and 500-mb charts and predetermined mathematical surfaces. A correlation coefficient thus obtained is simply the correlation between pressure or height data at the 56 grid points of a given chart and the corresponding 56 points of a mathematical surface, taken point by corresponding point.

The intensity of circulation parameter at 500 mb, S', is proportional to the standard deviation of the height data and is expressed as follows:

$$S' = \left[\Sigma X^2 - \frac{1}{N}(\Sigma X)^2\right]^{\frac{1}{2}} \qquad (17)$$

Note that this expression is part of the denominator of equation (16) so that it is simply a byproduct of the correlation computations.

FORECASTING EXAMPLE

The following example will serve to illustrate the use of the method. Given the sea-level and 500-mb charts for hurricane Daisy for 1200 GMT, August 28, 1958, and the past 12-hr movement, equations (14) and (15) are then used to obtain a 24-hr forecast of the future position of the storm. The sea-level and 500-mb charts are given in figures 91 and 92. Data are extracted from the charts at a grid of 56 points as shown in figure 91. With the storm center located at 30° N lat, the grid points are 4 deg lat and long apart with the grid extending 10° to the south of the center

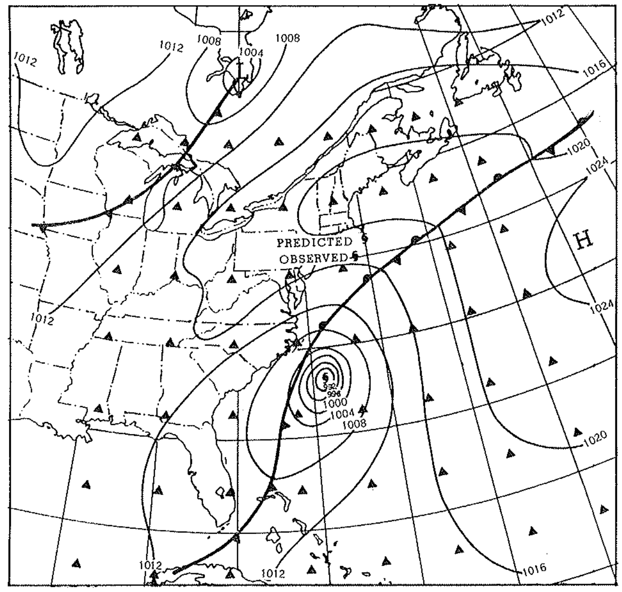


Figure 91.—Sea-level chart, 1200 GMT, August 28, 1958, showing current position of hurricane Daisy and the grid points indicated by solid triangles from which the pressure values given in table 15 are read. Also shown are the 24-hr predicted and observed positions of the storm.

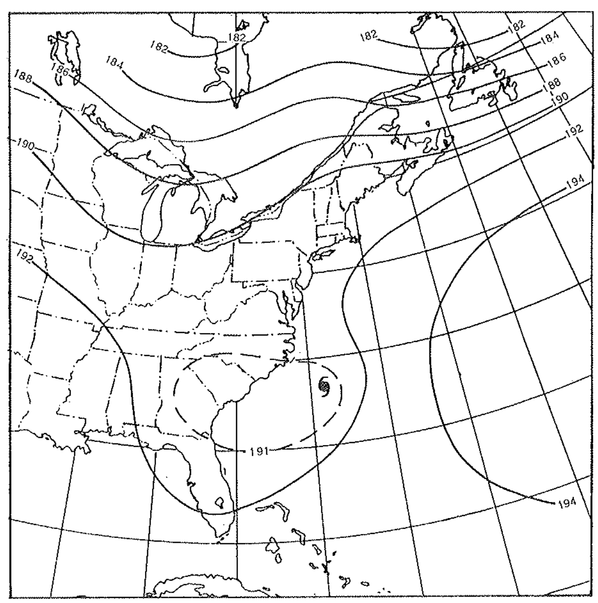


Figure 92.—Chart showing the 500-mb height lines for 1200 GMT, August 28, 1958. Data given in table 16 are read from this chart using the same grid shown in figure 91.

Table 15. Pressures in whole millibars read from the grid points after subtracting 1000.

									Row sums
	10	9	12	15	17	19	19	18	119
	11	13	16	19	21	22	22	21	145
	12	15	17	16	16	17	20	22	135
	14	15	13	8	9	16	20	23	118
	14	12	9	3	8	16	20	22	104
	13	12	10	10	13	16	19	20	113
	13	12	11	13	14	16	17	18	114
Column sums	87	88	88	84	98	122	137	144	848

and 14° to the north, east, and west. All computations are made on a desk calculator.

In order to reduce the size of the numbers involved in the calculations, a constant is subtracted from the reading at each grid point. Negative values are avoided. Thus, the data representing the sea-level chart may be obtained by subtracting 1000 from each pressure reading to give the array of values shown in table 15. Similarly, data are given in table 16 for the 500-mb chart.

CALCULATION OF CORRELATION COEFFICIENTS

Equation (16) is used to obtain the required values of z and z'. This expression is made up of three parts, the numerator and the two factors in the denominator. The first factor in the denominator is readily obtained using a desk calculator, where ΣX^2 is the sum of the squared values read from the 56 grid points of the sea level or 500-mb chart and where $\frac{1}{N}(\Sigma X)^2$ is the square of the sum of the same values divided by 56. For the north-south oriented mathematical surfaces, the second factor, ΣY^2, is the sum of the eight squared terms of the polynomials taken seven times (7x168 for F_1 and F_2, and 7x264 for F_3) and for the east-west oriented surfaces the factor is the sum of the seven squared terms taken eight times (8x28 for G_1, 8x84 for G_2, and 8x6 for G_3). For mathematical surfaces defined by the cross multiplication of two polynomials, the factor ΣY^2 must be computed by summing all 56 squared terms (e.g., the terms given in table 14).

The numerator, ΣXY, is the sum of 56 products made up by multiplying the individual values of the mathematical surface (as given in table 13) with the corresponding values of the sea-level or 500-mb chart (as given in table 15 or 16). For most correlation coefficients, the computation can be considerably shortened. This comes about from the fact that the north-south and east-west oriented mathematical surfaces are made up of columns (or rows) of the same numbers. Thus, for the north-south oriented surface the numerator can be written

$$\Sigma XY = \overset{\text{column 1}}{Y\Sigma X} + \overset{\text{column 2}}{Y\Sigma X} \;\ldots\ldots\; \overset{\text{column 8}}{Y\Sigma X} \qquad (18)$$

where the ΣX's are the sums of the columns as

Table 16. Heights in 10's of feet (first figure omitted) read from the grid points of the 500-mb chart after subtracting 860.

									Row sums
	18	8	10	20	29	30	20	15	150
	37	32	38	43	48	52	56	56	362
	55	50	52	54	57	66	77	82	493
	62	59	52	53	57	71	88	95	537
	65	60	50	50	55	72	88	90	530
	65	61	60	61	64	72	82	85	550
	61	65	72	72	74	74	75	80	573
Column sums	363	335	334	353	384	437	486	503	3195

Table 17. Summary of computational values entering into the evaluation of the required correlation coefficients. Also given are the additional parameters required for substituting into the equations.

For given z	ΣXY	$\Sigma X^2 - \frac{1}{N}(\Sigma X)^2$	ΣY^2	Value of z
		(For sea-level chart)		
z_1	-760	1065	1176	-.679
z_2	302	"	1176	.270
z_6	-110	"	224	-.225
z_{11}	-192	"	4704	-.086
		(For 500-mb chart)		
z'_1	-2075	23,899	1176	-.391
z'_3	589	"	1848	.089
z'_6	1682	"	224	.727
z'_7	-1602	"	672	-.400

Additional parameters: $P_u = -0.9$, $P_v = 3.0$, and $S' = 154.6$

given in tables 15 and 16 and Y's are the corresponding terms of the orthogonal polynomials (e.g., as in table 13). For the east-west oriented surfaces, a similar expression can be written for the seven rows. In practice, the computations may be accomplished by entering the terms of the polynomials along the edge of a card (along the horizontal edge for the F polynomials and along the vertical edge for the G polynomials) with the spacing the same as for the column (or row) sums. The sums and the corresponding polynomial terms are then adjacent and the multiplications can be readily carried out and accumulated to give the value of the numerator. For coefficients of correlation based on the cross multiplication of two polynomials (e.g., the data given in table 14), the full computational procedure for the calculation of a correlation coefficient is carried out.

SUMMARY OF COMPUTATIONS

Using the information given in tables 12 and 14 concerning the orthogonal polynomials and that in tables 15 and 16 concerning the sea-level and 500-mb charts, the values of the required correlation coefficients and the intensity of circulation parameter are obtained for substituting into the forecasting equations. A summary of the computations of these quantities is given in table 17.

The parameters given in table 17 are then substituted into equations 14 and 15 to give $u = -2.91$ and $v = 7.42$. This forecast position had been entered in figure 91. Also shown is the verifying position of the storm.

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